

Numerical Prediction of Meteoric Infrasound Signatures

Marian Nemec

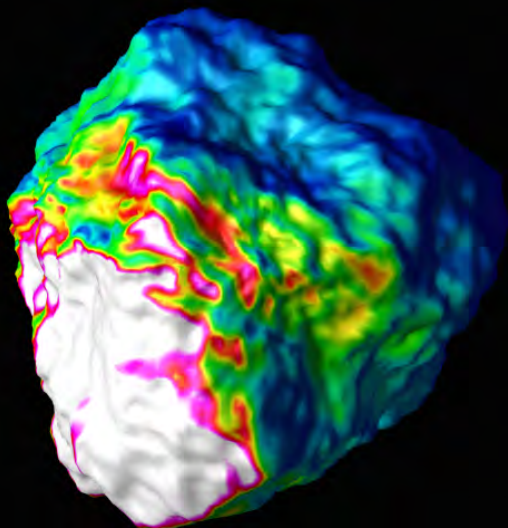
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Michael Aftosmis

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USA*

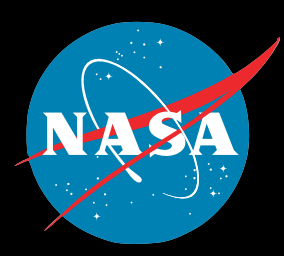
Peter Brown

*University of Western Ontario
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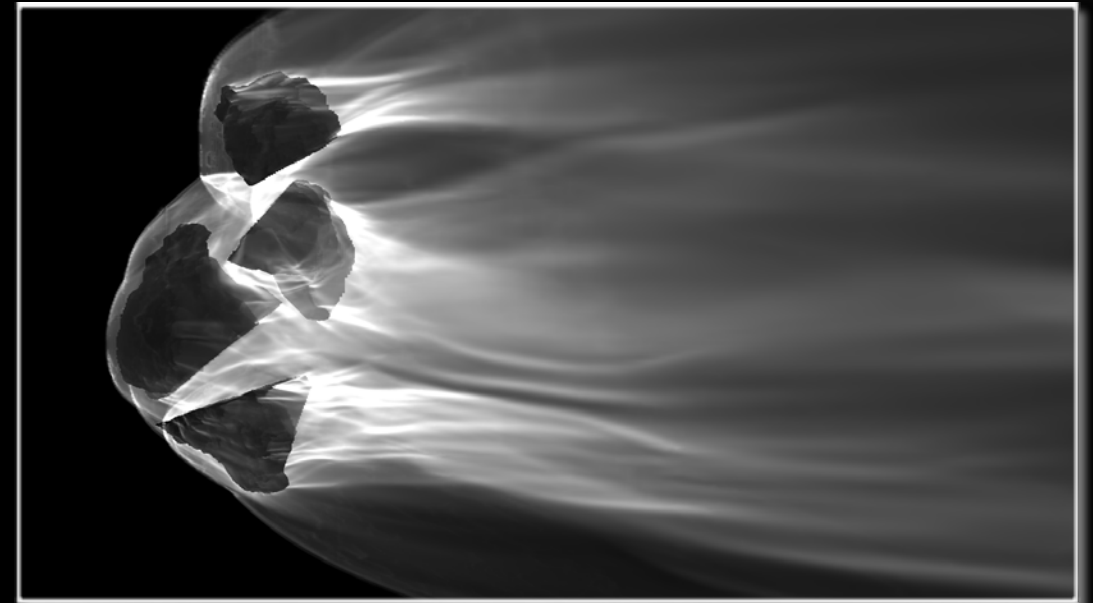
Meteoroids 2016

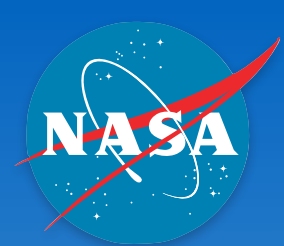
Noordwijk, June 8, 2016



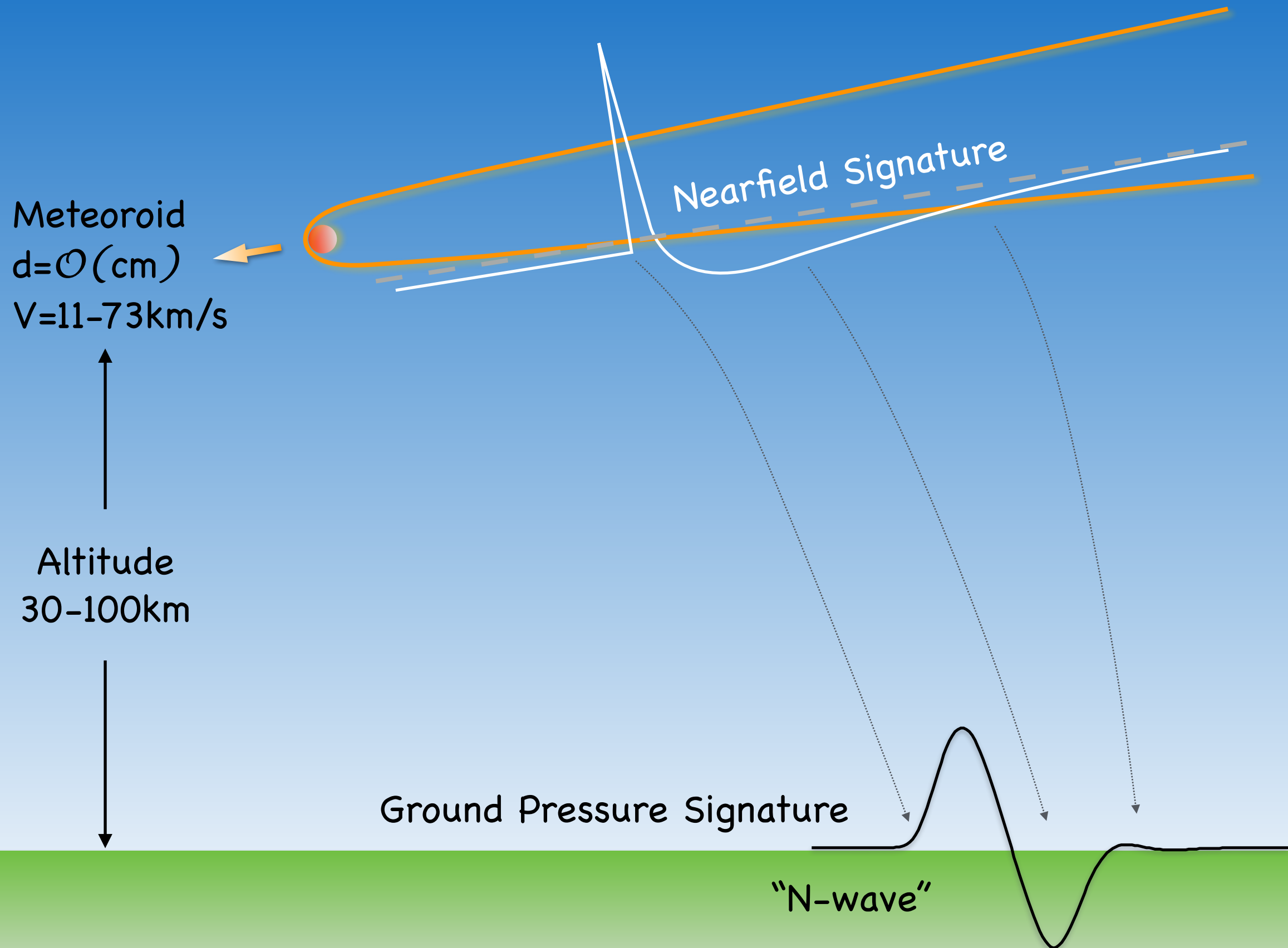
Motivation and Objectives

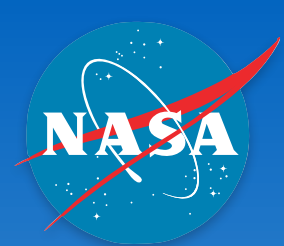
- **Meteors: steady source of infrasound**
 - Meteoroid speed: 11-73 km/s
 - Meteoroid size: mm - m's
 - Strong bow-shock and complex flowfield
- **New constrained regional dataset**
 - Over 80 infrasound signatures collected by the Southern Ontario Meteor Network (SOMN), *Silber 2014*
- **Infrasound-based mass estimates verify optical and radar observations**
 - Bow-shock essentially independent of ablation process
 - Analytic model (*ReVelle 1976*): significant variability in predicting infrasonic mass
- **How accurate are numerical models? How can they help?**
 - Promising simulations of *Henneton et al. 2015*
 - Relax assumptions required to formulate analytic models



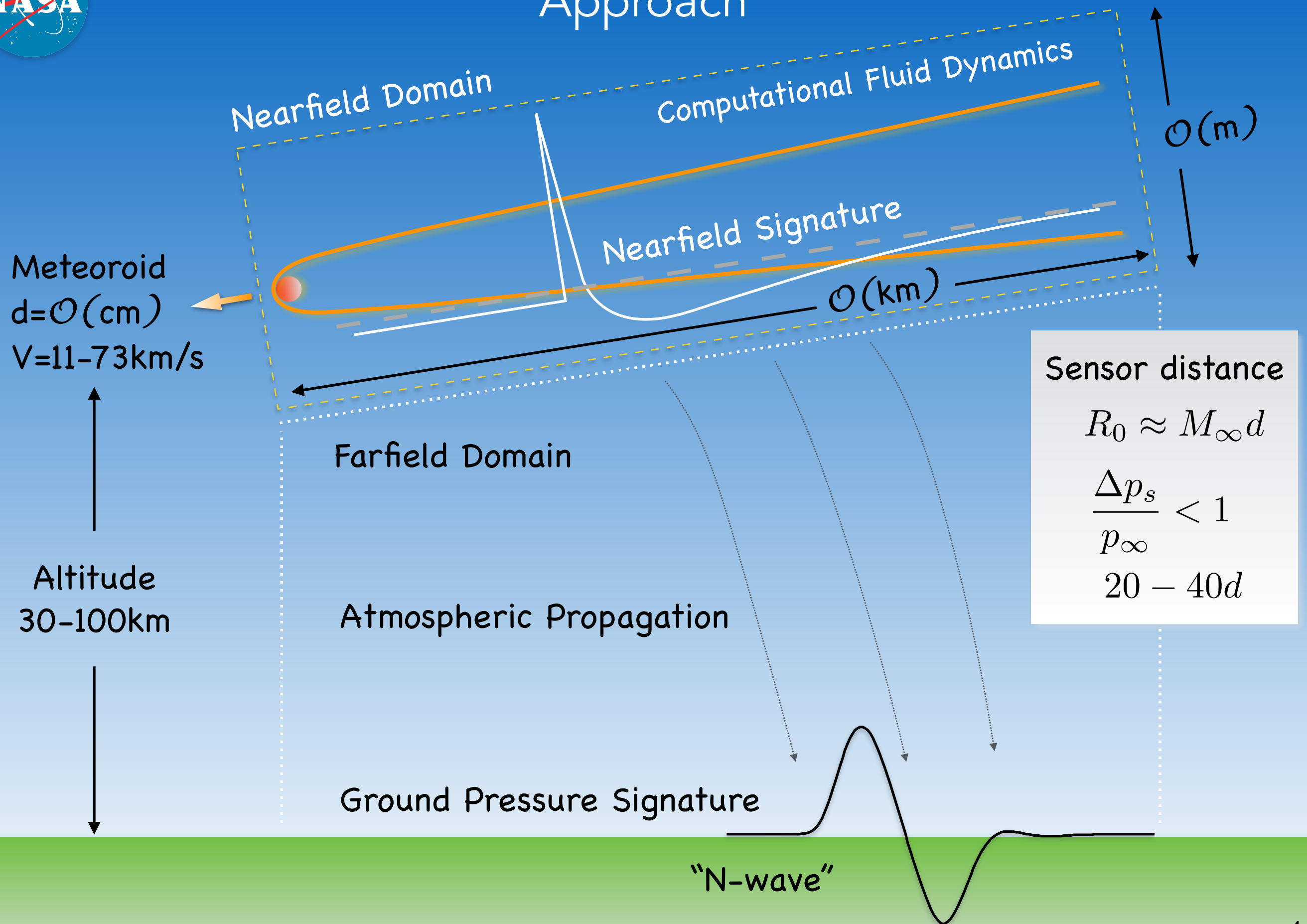


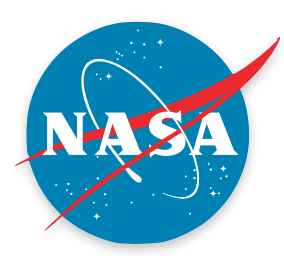
Approach



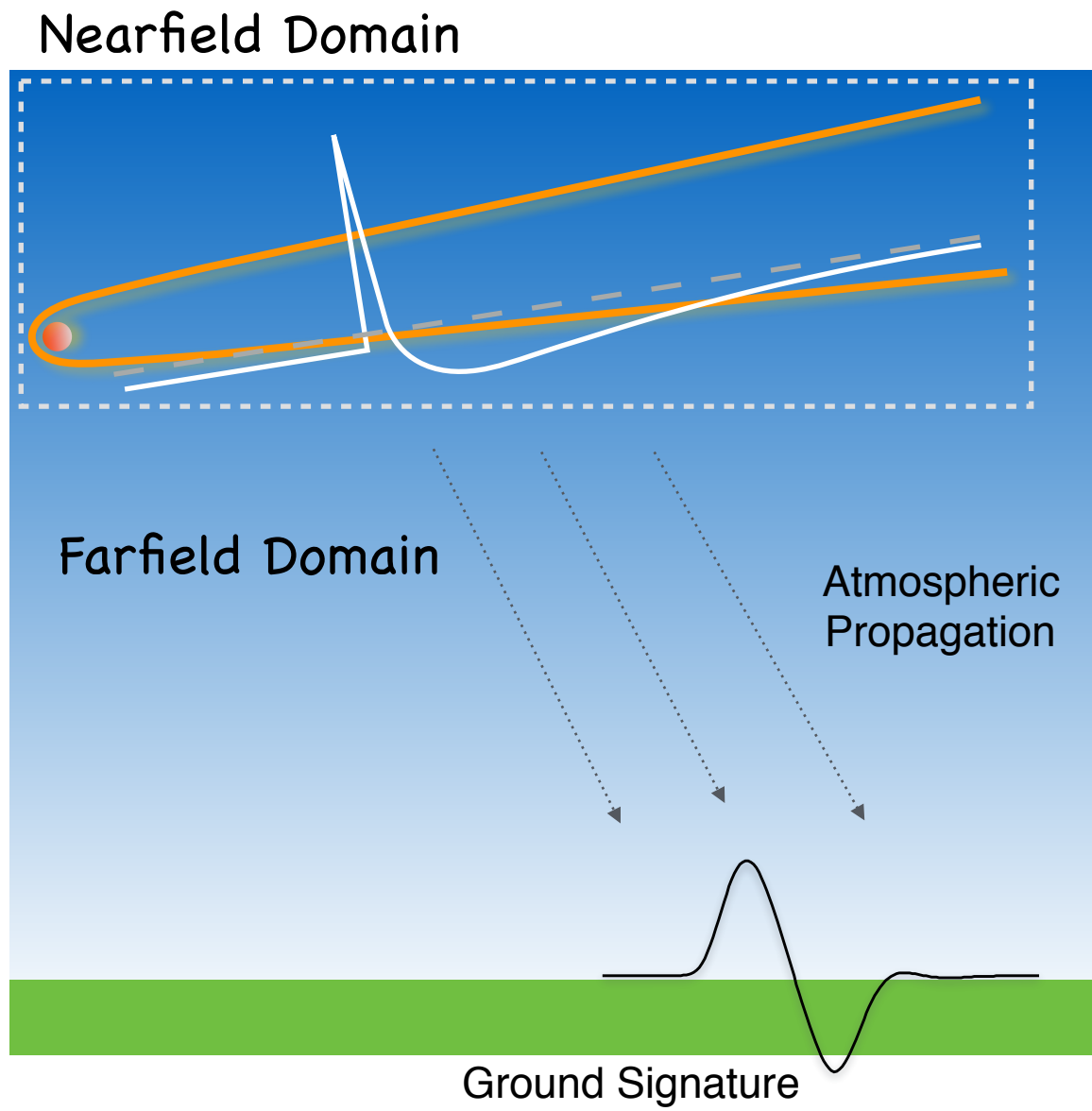


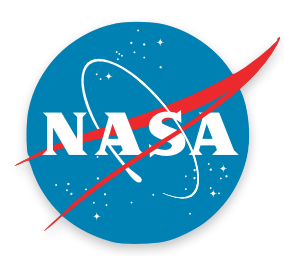
Approach



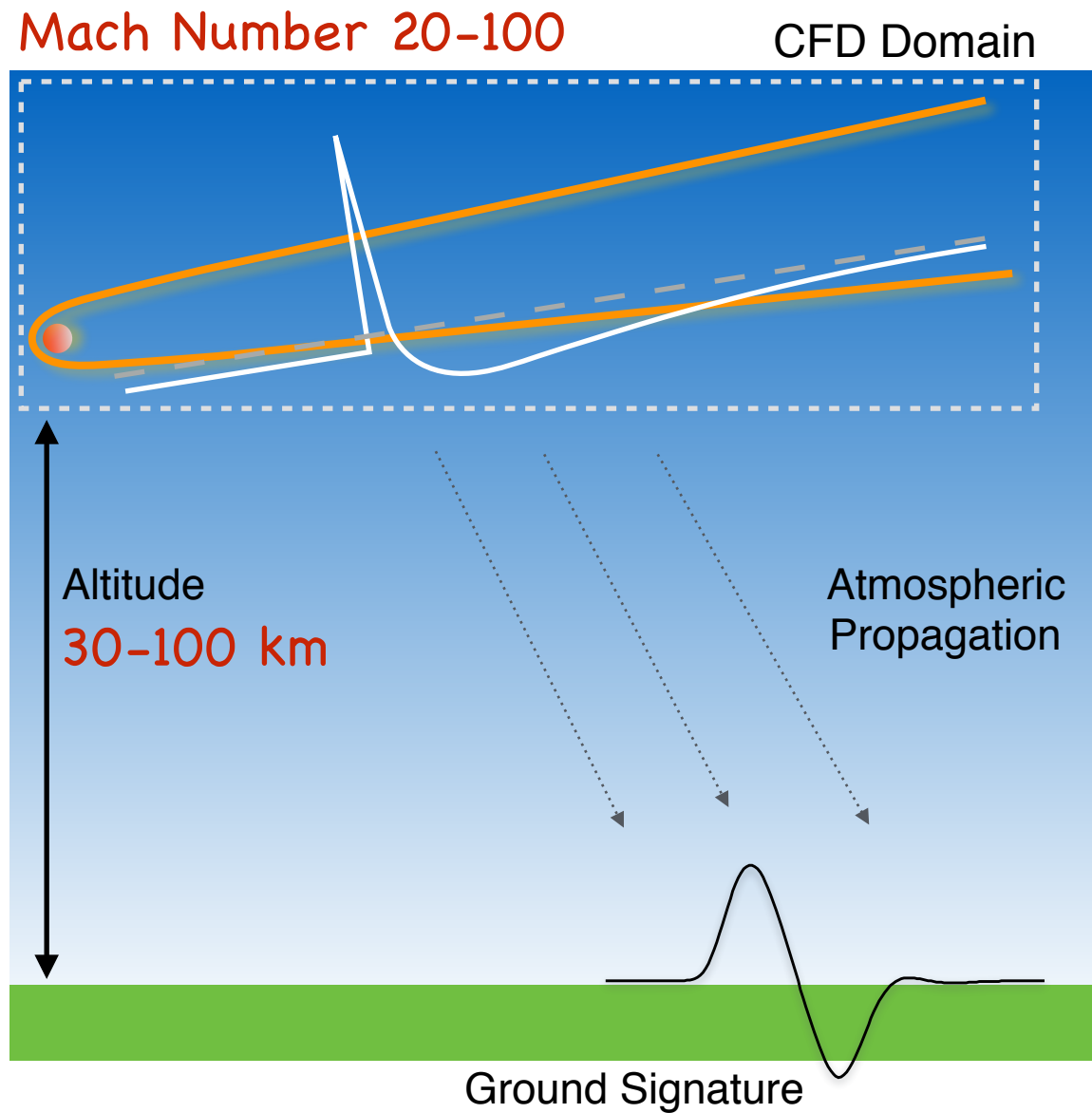


Approach

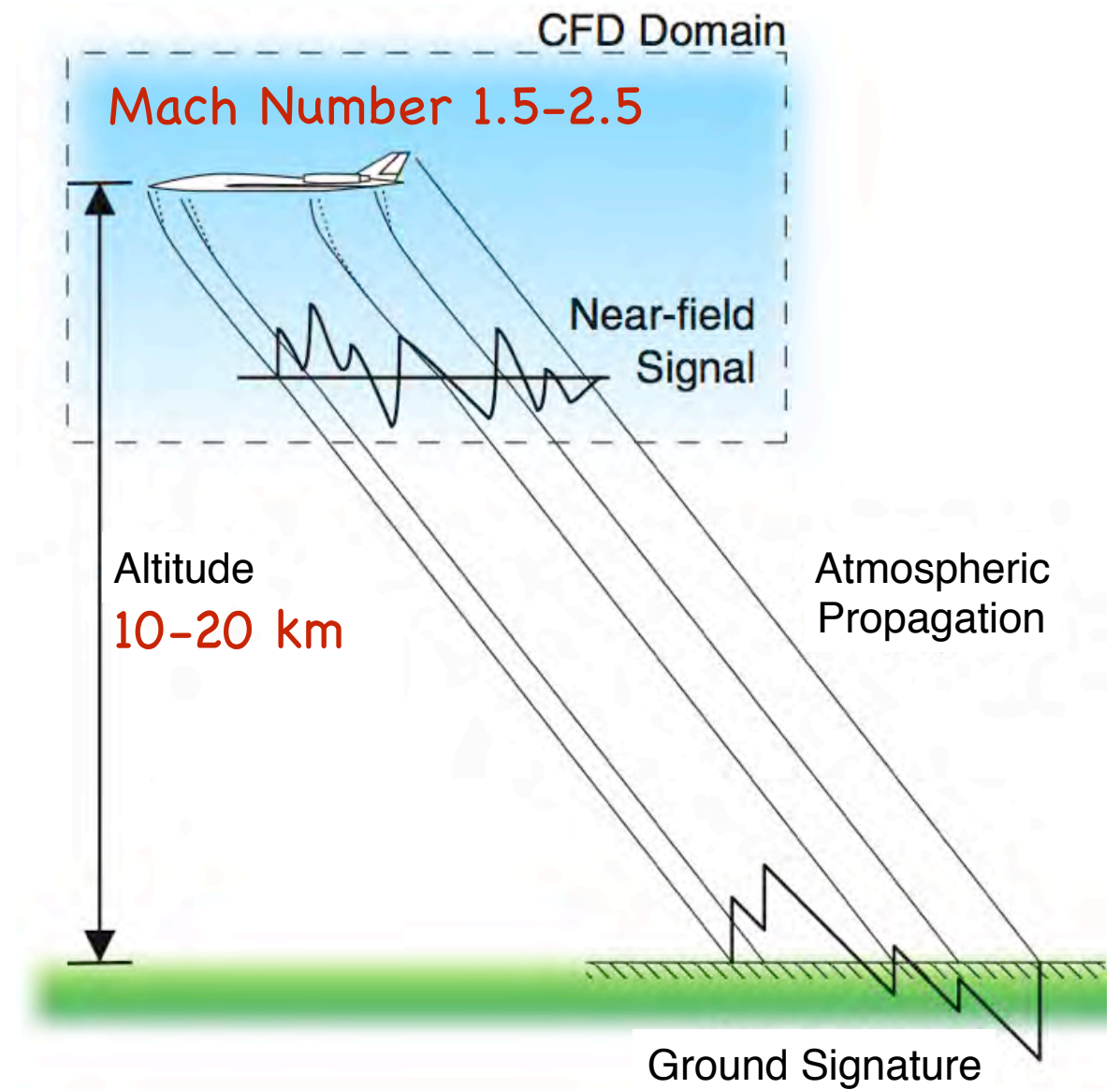




Approach

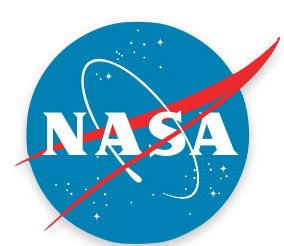


Typical overpressure $< 1 \text{ Pa}$



Typical overpressure $> 10 \text{ Pa}$

Leverage tools and experience from aircraft sonic-boom analysis and low-boom design



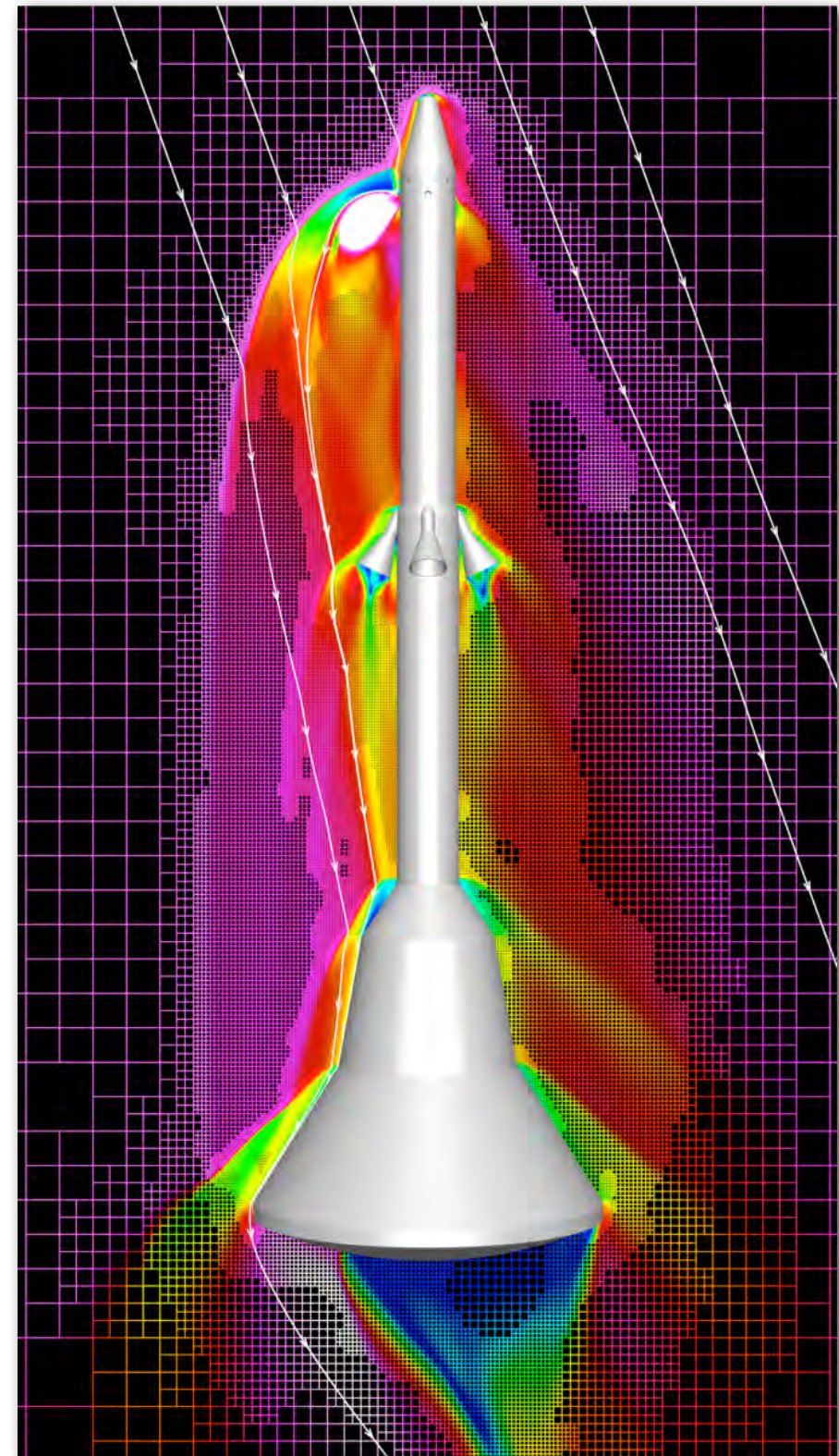
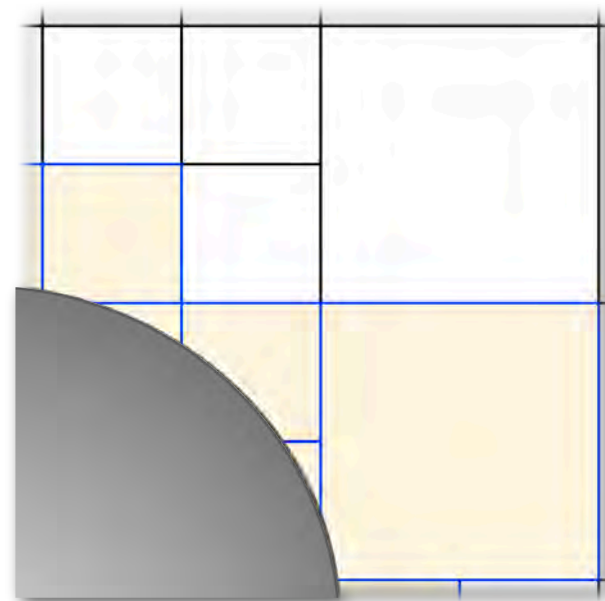
Nearfield Solver: Cart3D

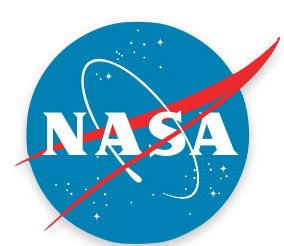
Assumptions

- Air in thermochemical equilibrium
- Steady inviscid flow
 - Euler equations

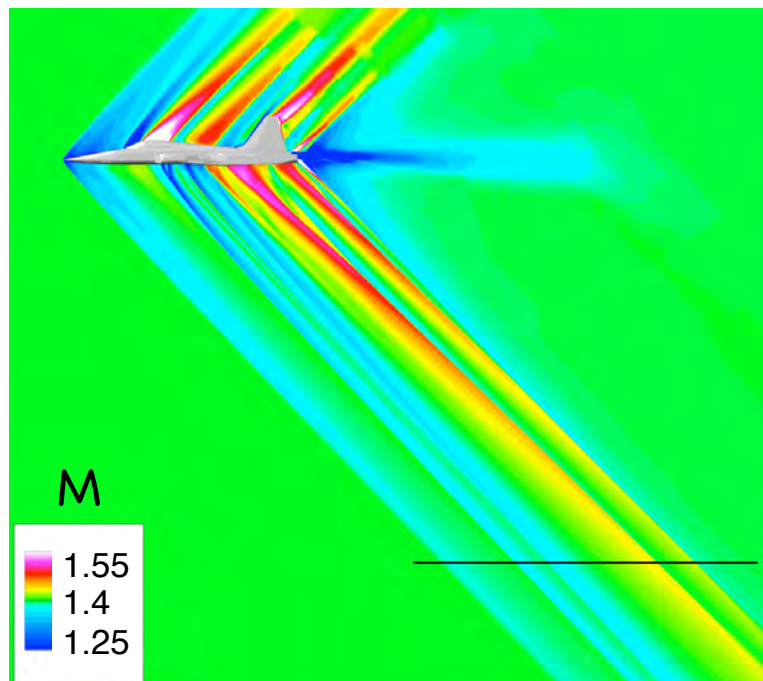
Flow Simulation

- Cartesian mesh with cut cells
- Second-order finite-volume spatial discretization
- Adaptive mesh refinement
 - Method of adjoint weighted residuals: mesh tailored to minimize discretization error in selected outputs
- Broad use throughout NASA, US Government, industry and academia





Nearfield Signature Prediction with Cart3D



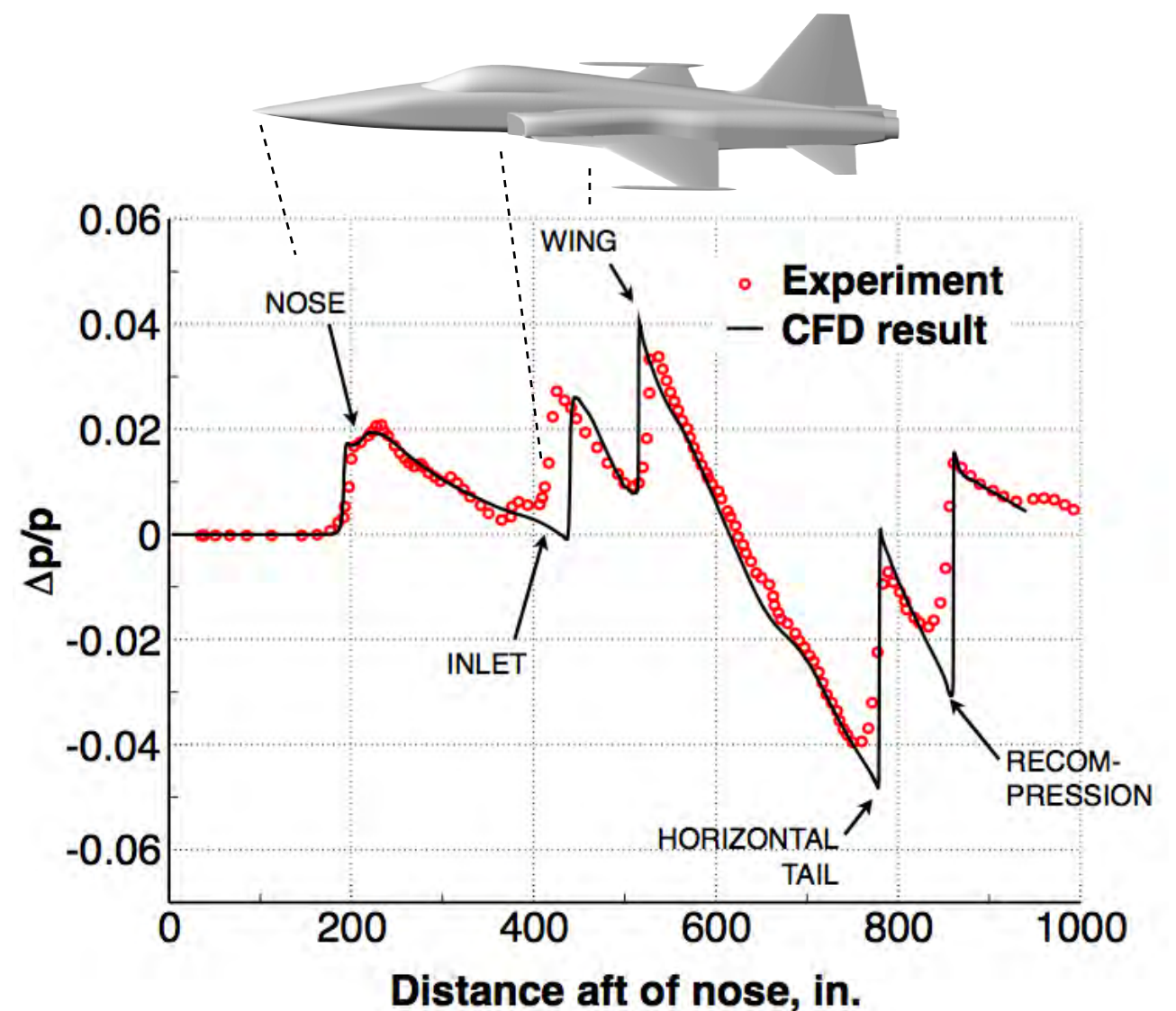
F5-E Nearfield Pressure Flight Test

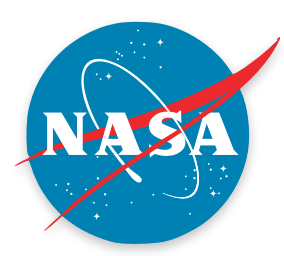
Output of interest: $J = \int_0^L \left(\frac{\Delta p}{p_\infty} \right)^2 ds$

- Mach number (M) 1.4
- Separation distance is roughly 2 aircraft lengths



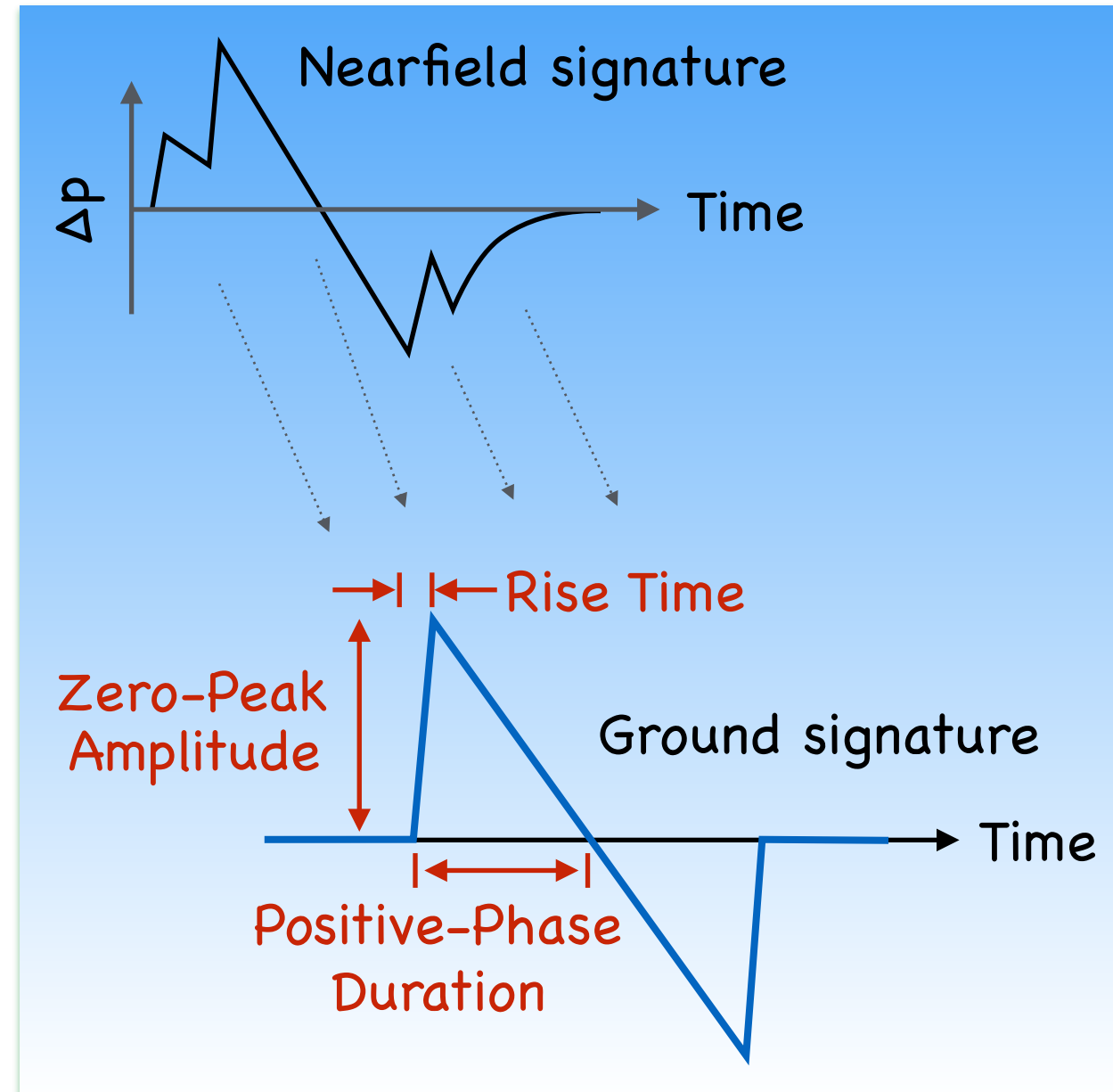
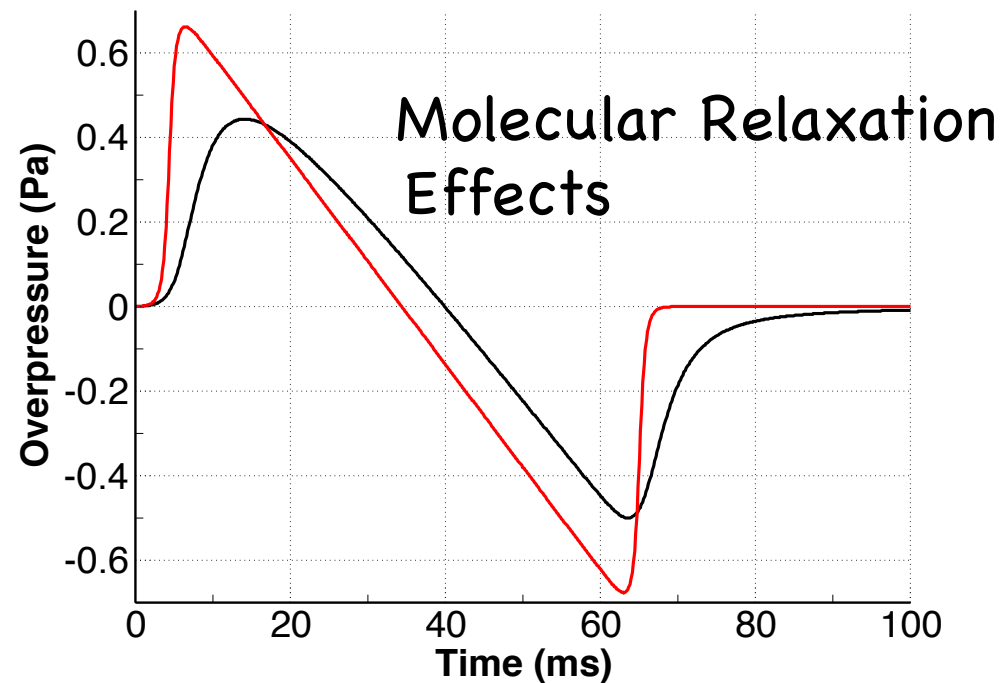
Wintzer, Nemec & Aftosmis, 2008



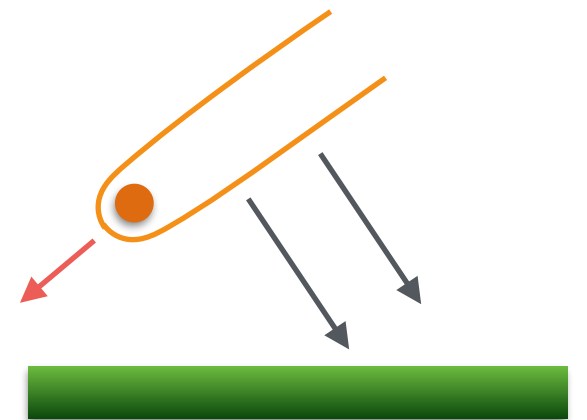


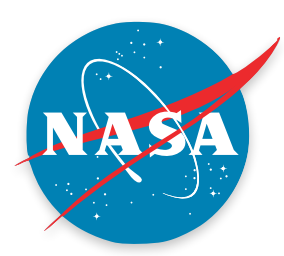
Farfield Signal Propagation: sBOOM

- Augmented Burgers equation
 - Nonlinear steepening
 - Thermoviscous absorption
 - Molecular relaxation



- User specified temperature, wind and humidity profiles
- Ray tracing via geometric acoustics
- Primary signature only (no secondary reflections)





Results

Part A. Stardust Entry

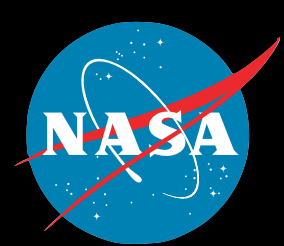
- Artificial meteor (12.5 km/s)
- Well-defined geometry and trajectory
- Multiple pressure-signature records



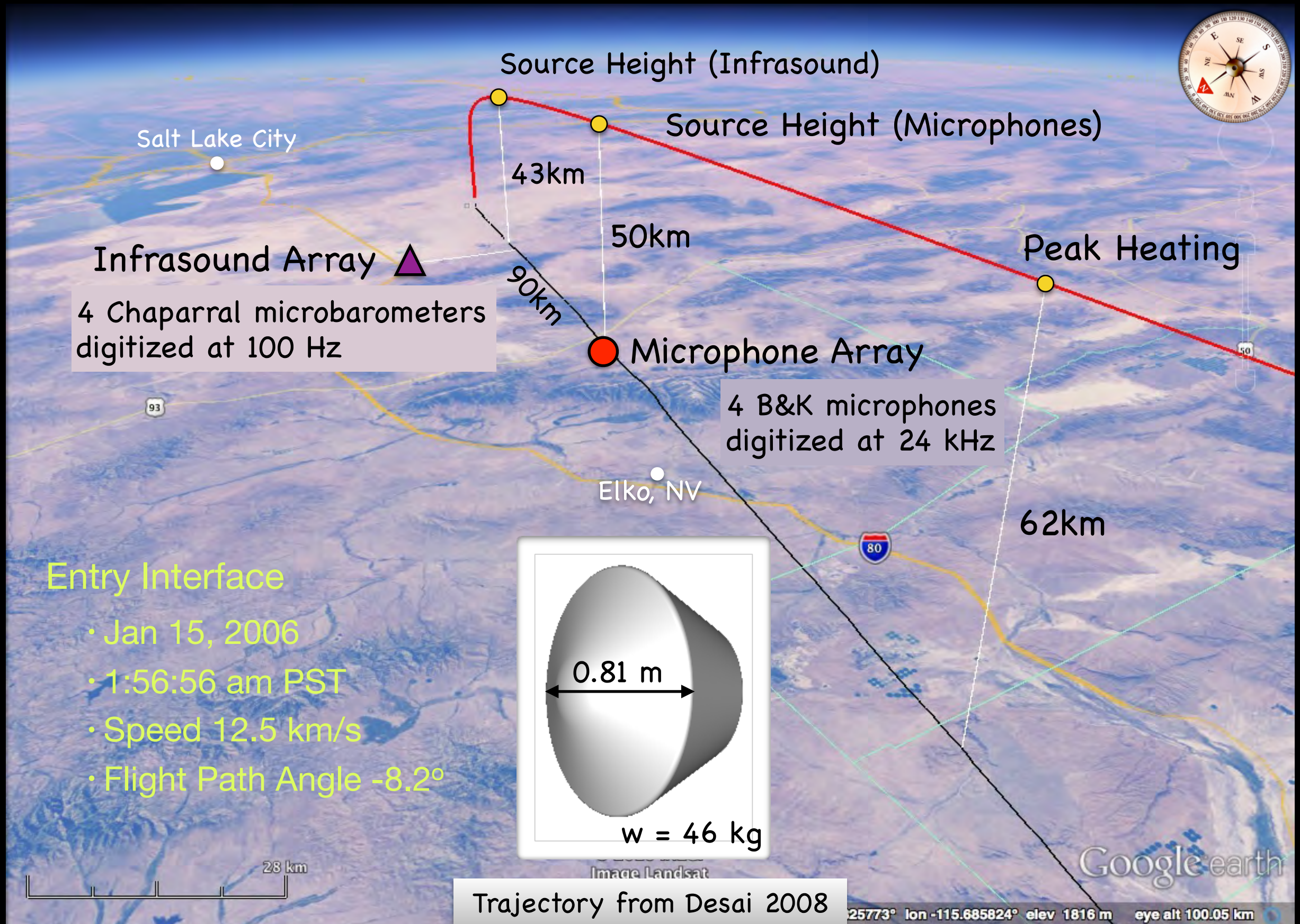
Part B. SOMN Infrasound Dataset

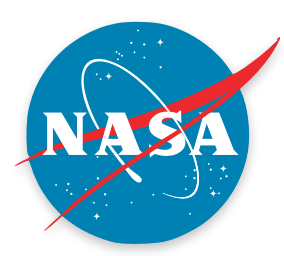
1. Meteor 20081028
 - Single infrasonic arrival
2. Meteor 20090428
 - Multiple arrivals
 - Steeper and faster entry



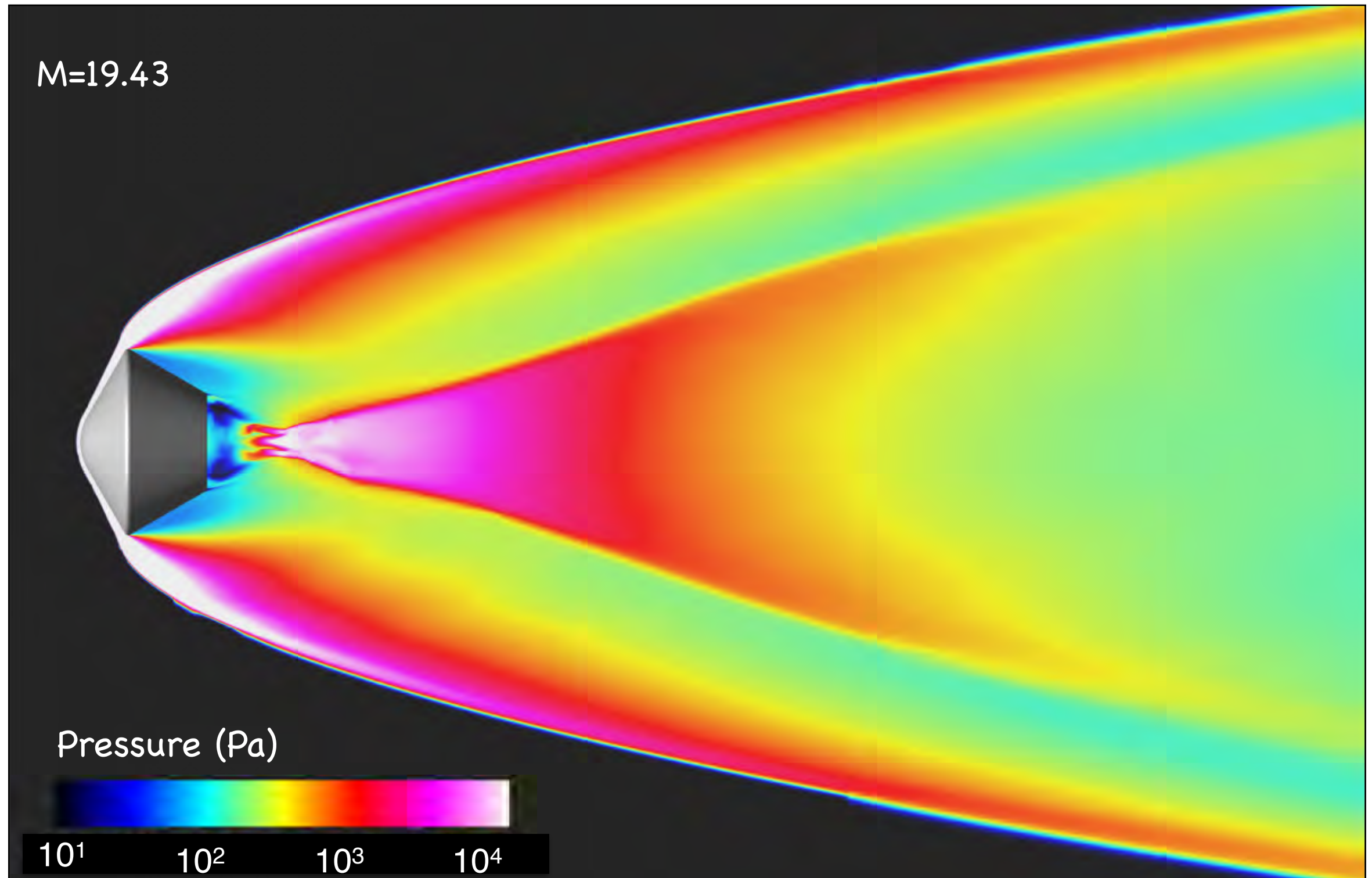


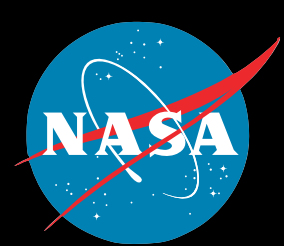
Stardust — Artificial Meteor





Nearfield Pressure





Nearfield Signatures

Infrasound Array
Source Height

Altitude 43 km
Velocity 3 km/s
M 9.5

Microphone Array
Source Height

Altitude 50.4 km
Velocity 6.4 km/s
M 19.4

90km

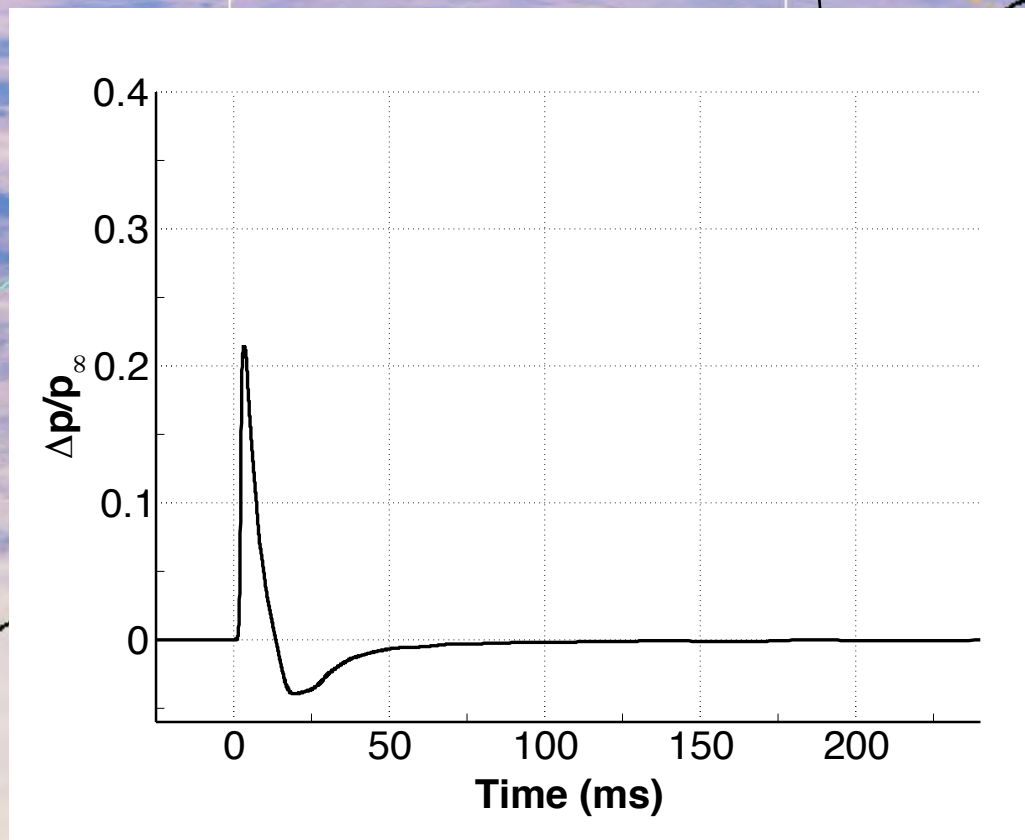
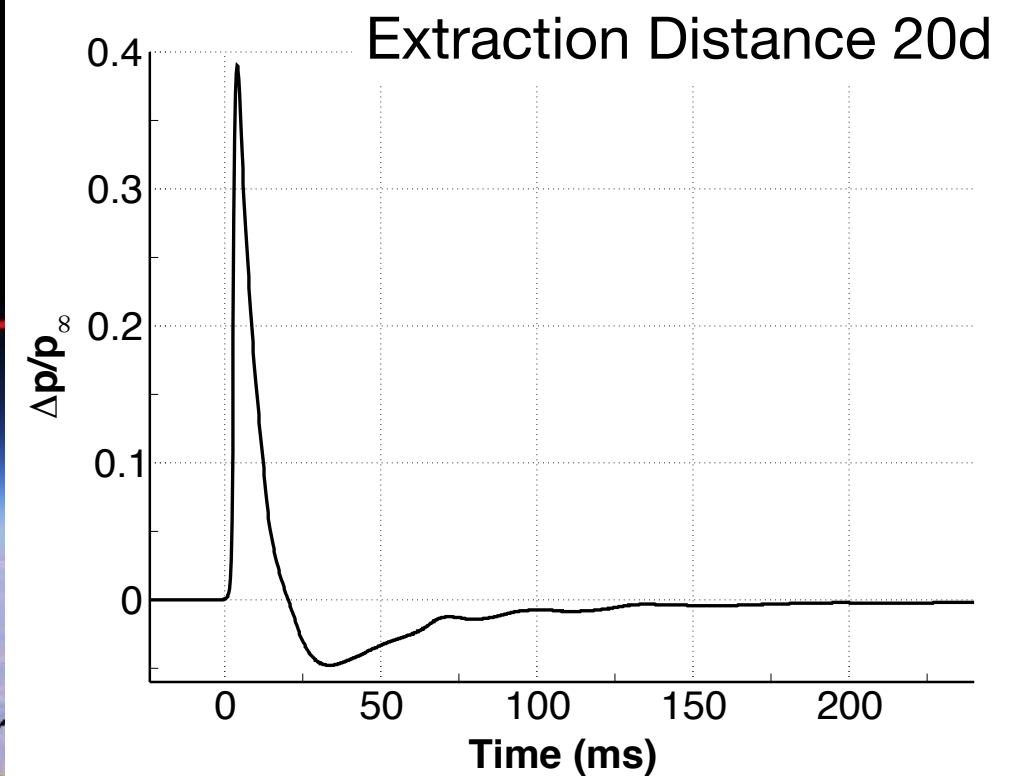
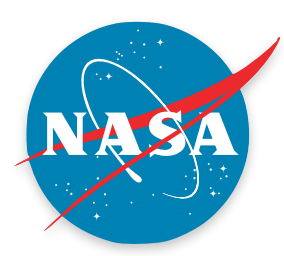
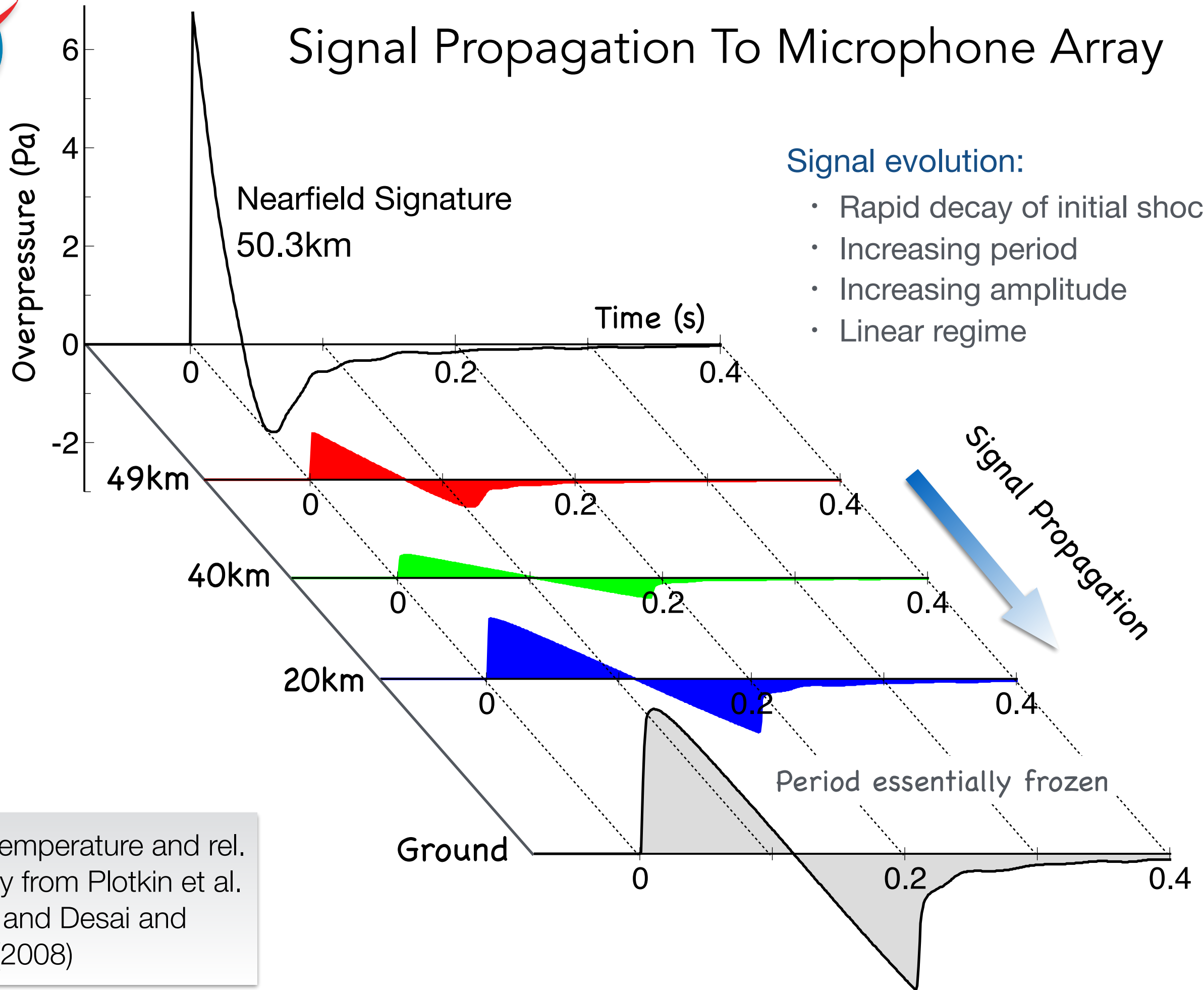


Image Landsat
Data LDEO-Columbia, NSF, NOAA

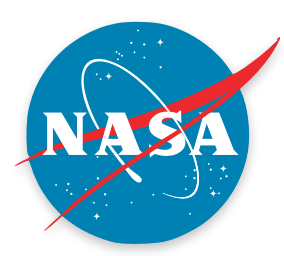
Imagery Date: 12/13/2015 lat 40.475716° lon -115.081961° elev 1839 m eye alt 64.34 km



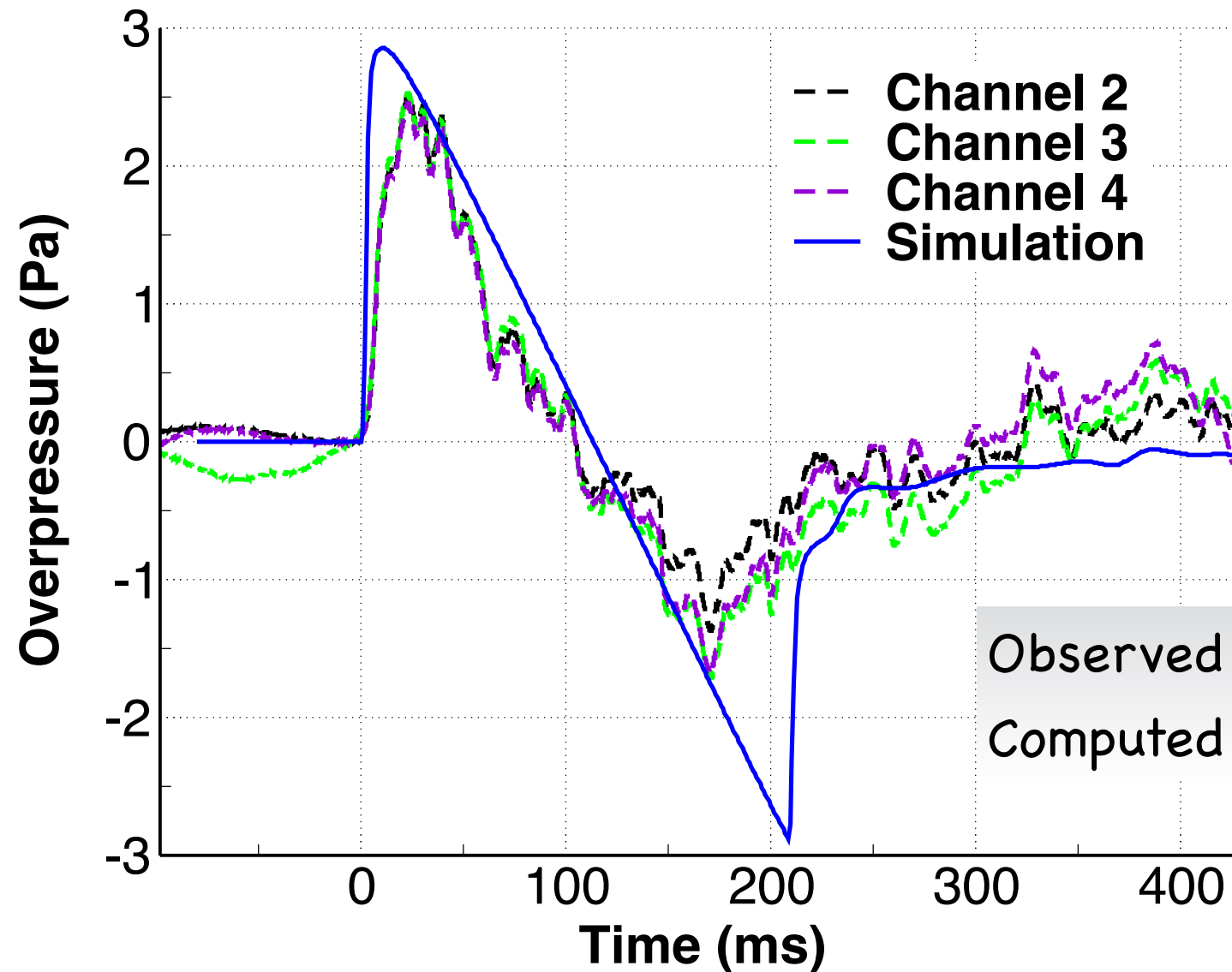
Signal Propagation To Microphone Array



Wind, temperature and rel. humidity from Plotkin et al. (2006), and Desai and Qualls (2008)



Microphone Array Comparison



M 19.4

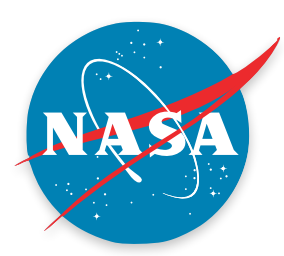
Speed 6.4 km/s

Off-track 4°

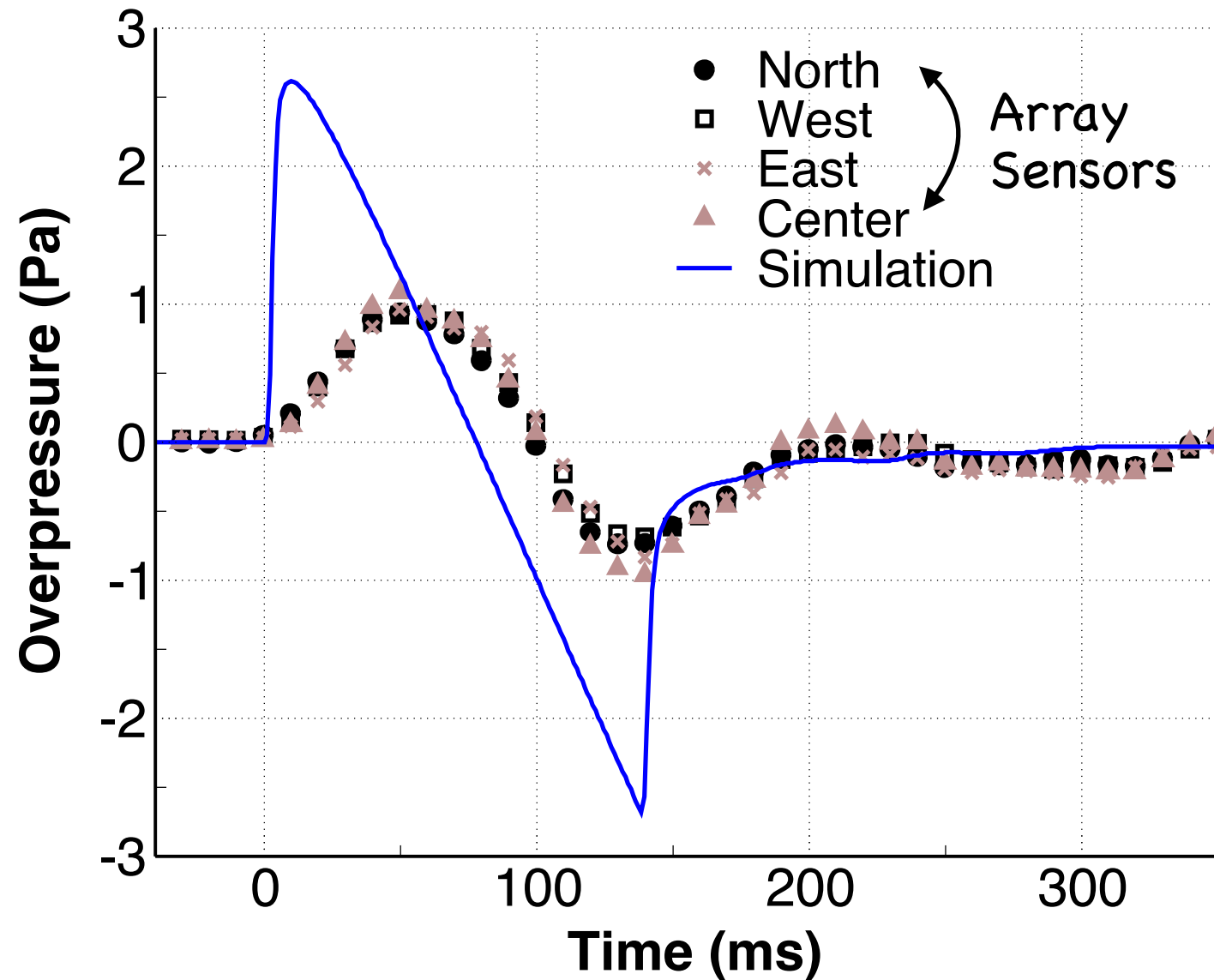
Altitude 50.4 km

Observed travel time: 161 s
Computed travel time: 162.6 s

- Excellent prediction of period and amplitude
- Measured signature more asymmetric (expansion not as deep)



Infrasound Array Comparison



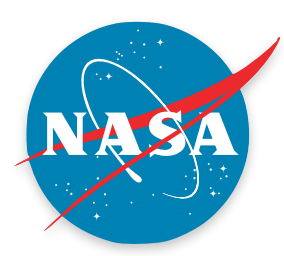
M 9.5

Speed 3 km/s

Off-track 38°

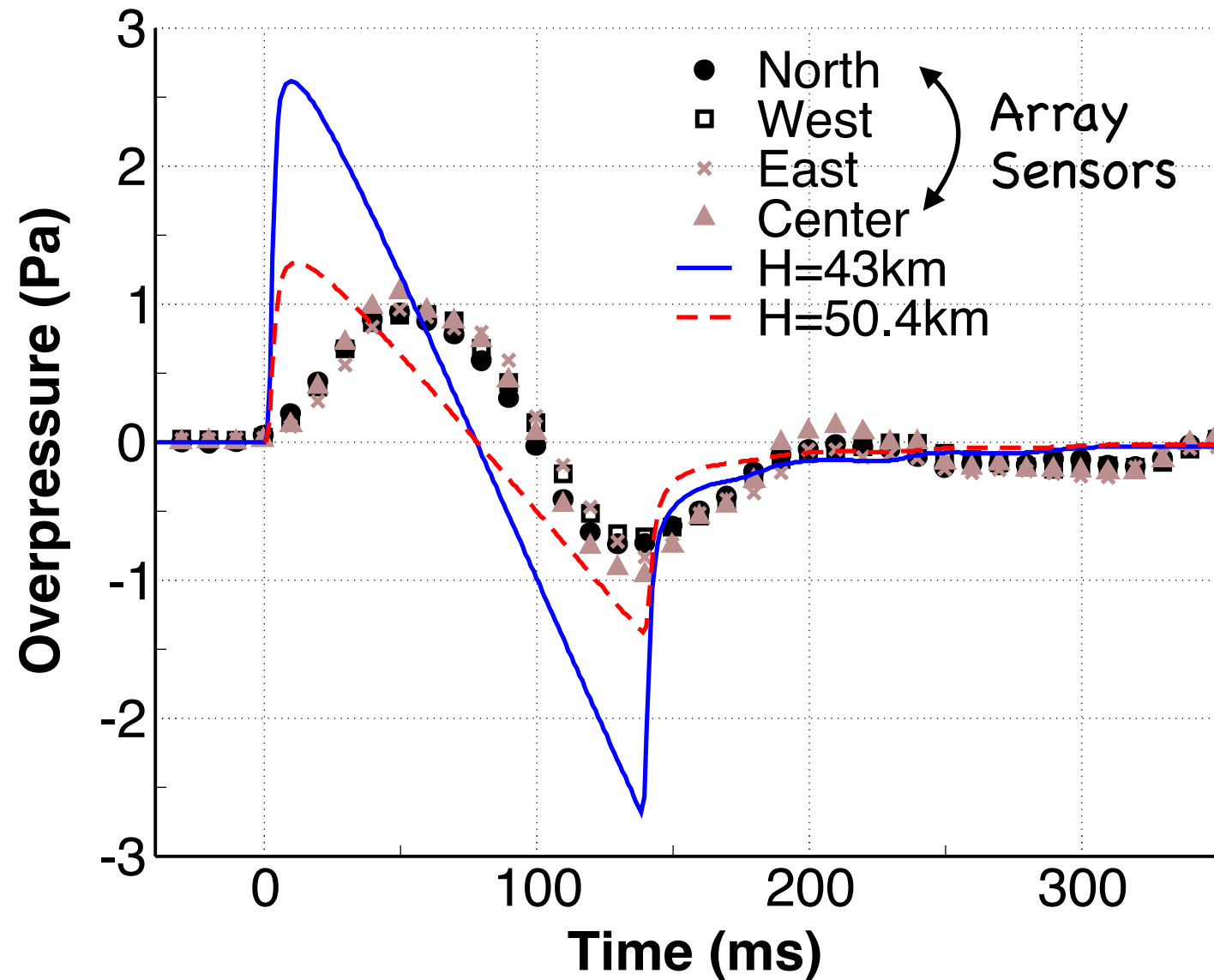
Altitude 43 km

- Observations show much longer rise time and lower amplitude
- Some agreement on slope in expansion region



Effect of Source Height

Infrasound Array Location



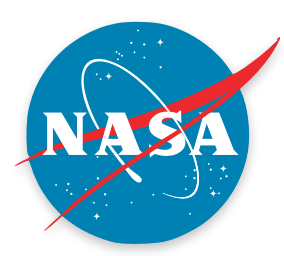
M 9.5

Speed 3 km/s

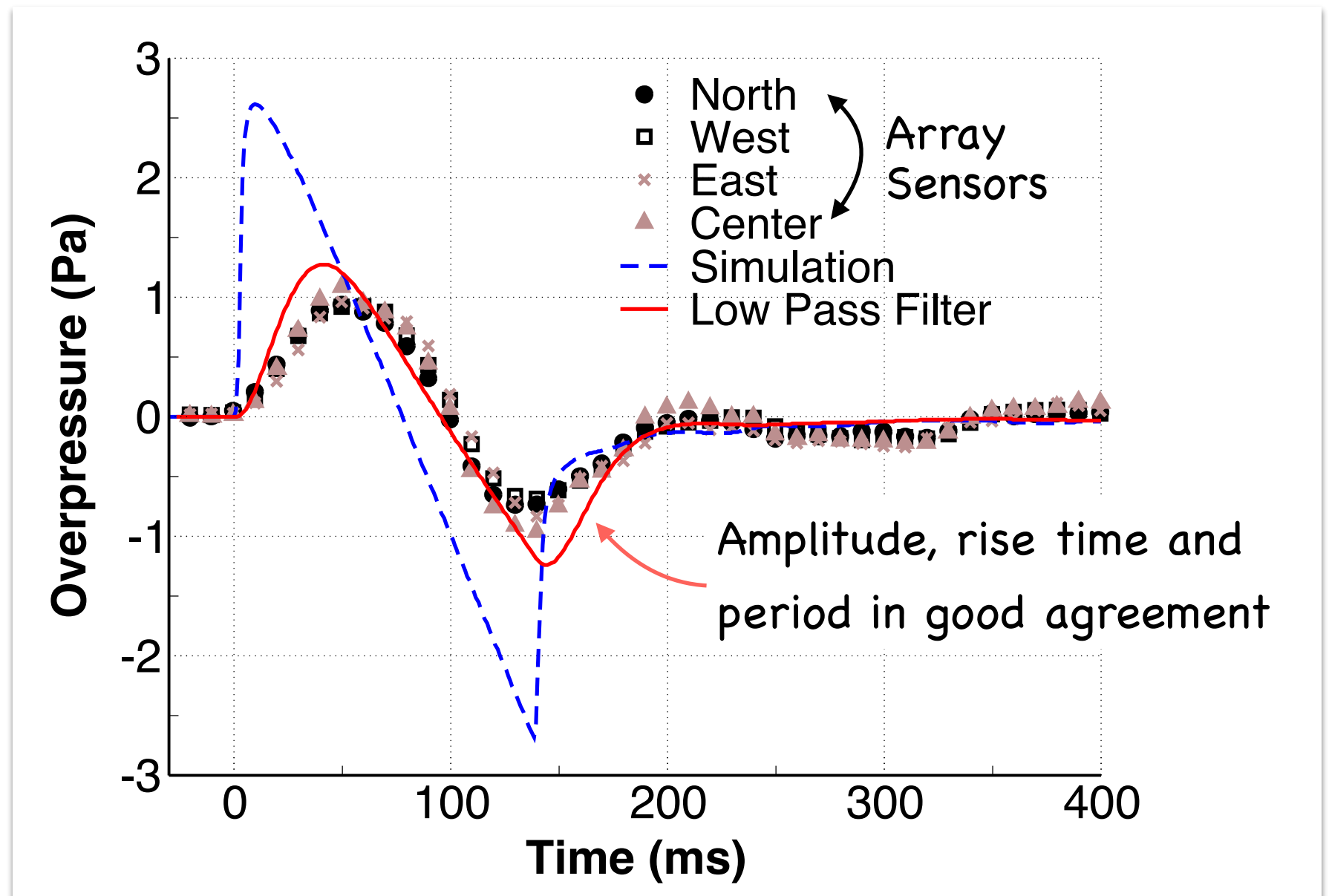
Off-track 38°

Altitude 43 km

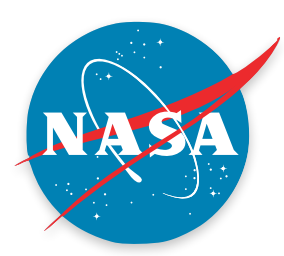
- To achieve correct signal attenuation requires unrealistic source height
- Rise time remains inaccurate



Account for Array Local Response



- Microbarometer: flat response to 200 Hz
- Digital sample rate 100 Hz
- Porous, 16 m long, soaker hoses
- Attenuate amplitude (0.6x) and filter with second-order Butterworth low-pass filter (15Hz)



Results

Part A. Stardust Entry

- Artificial meteor (12.5 km/s)
- Well-defined geometry and trajectory
- Multiple infrasound records



Part B. SOMN Infrasound Dataset

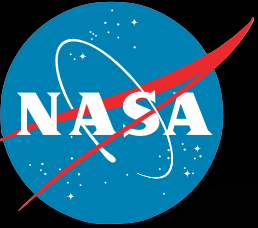
1. Meteor 20081028

- Single infrasonic arrival
- Low entry angle at 15.8 km/s

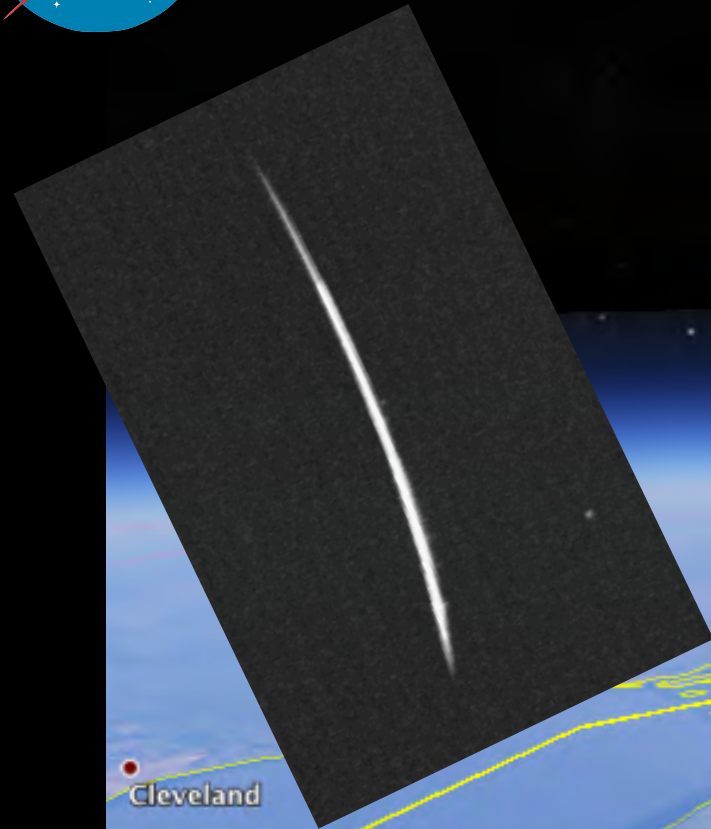
2. Meteor 20090428

- Multiple arrivals
- Steeper and faster entry





Meteor 20081028 Photometry Data



Start

81km

Flight Path

End

Ideal validation case

- Low speed: 15.8 km/s
- Low flight path angle: 32.9°
- Good mass estimate: 0.11kg
- Equivalent diameter 7cm

Assume inertial trajectory

- Constant speed
- Constant flight path
- No fragmentation

43.2km

62km

41km

Infrasound Array

Elev. 322m

London

Stratford

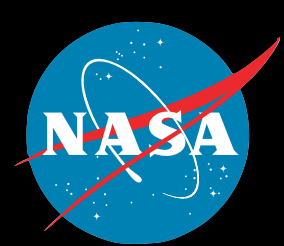
© 2015 Google
Image Landsat
Image NOAA

Data SIO, NOAA, U.S. Navy, NGA, GEBCO

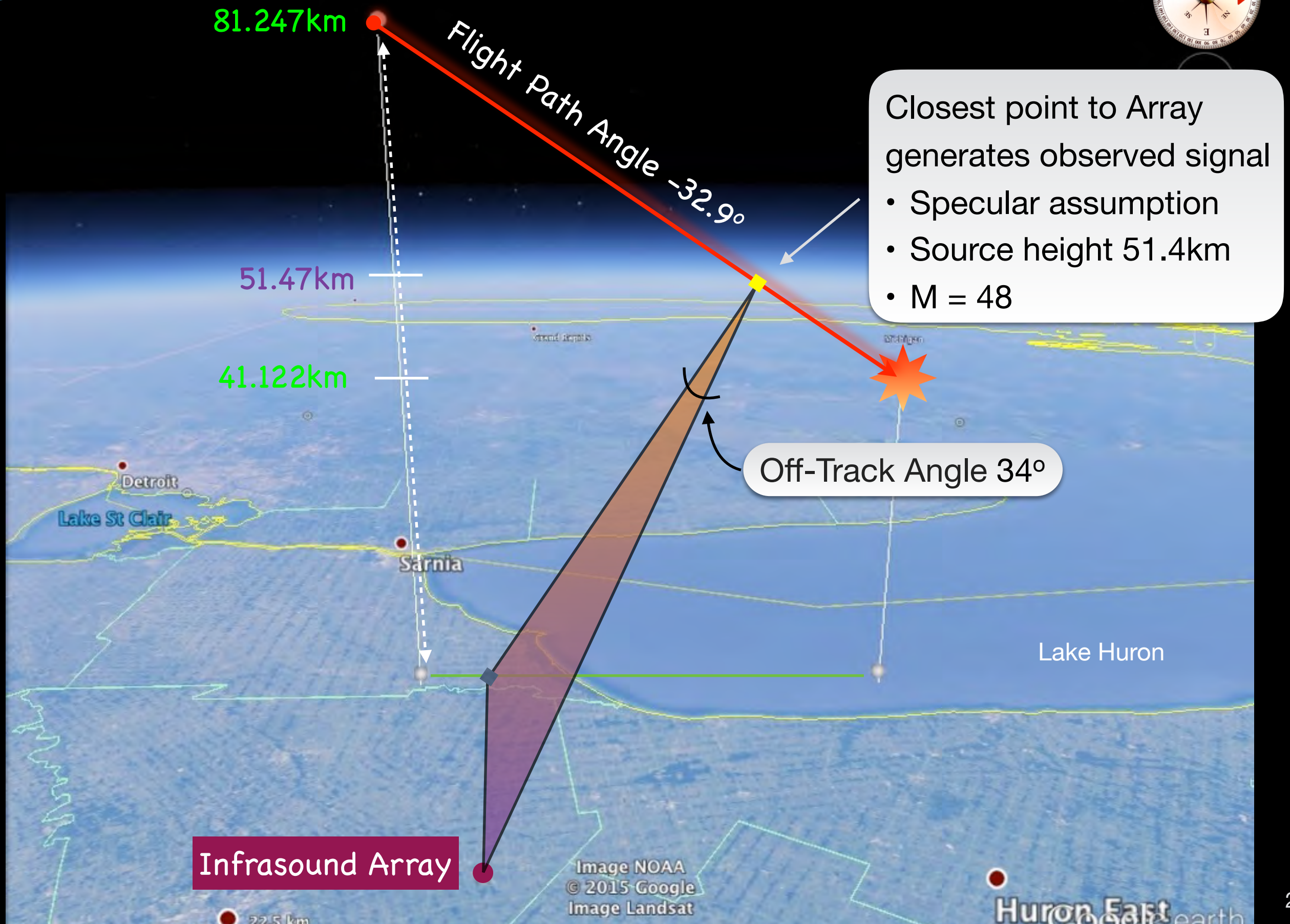
Lake Huron

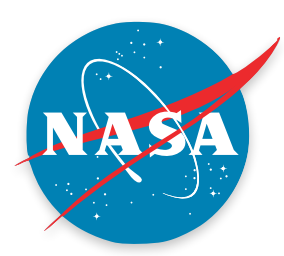
Google earth

24.8 km

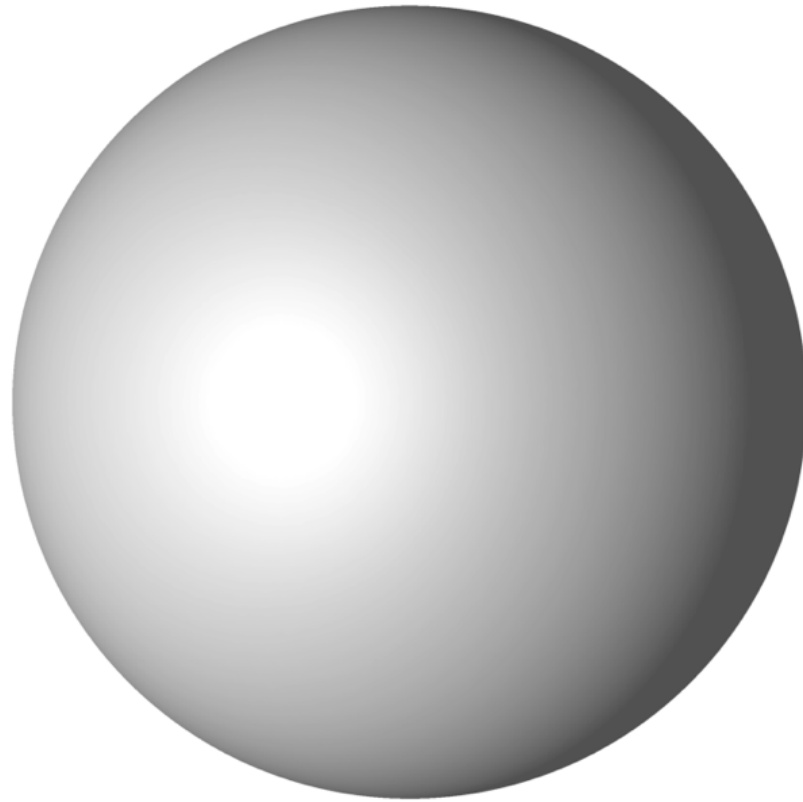


Trajectory Overview and Source Height



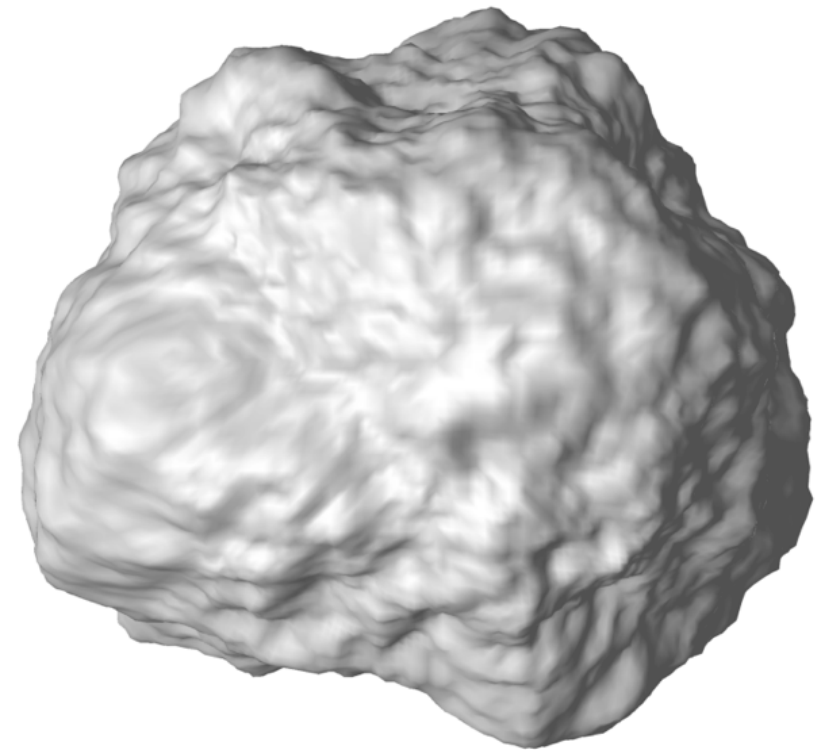


Meteoroid Geometry



$d = 0.07 \text{ m}$

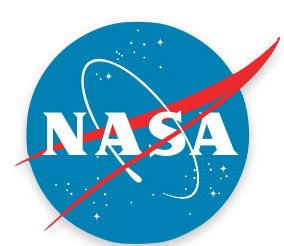
"Sphere"



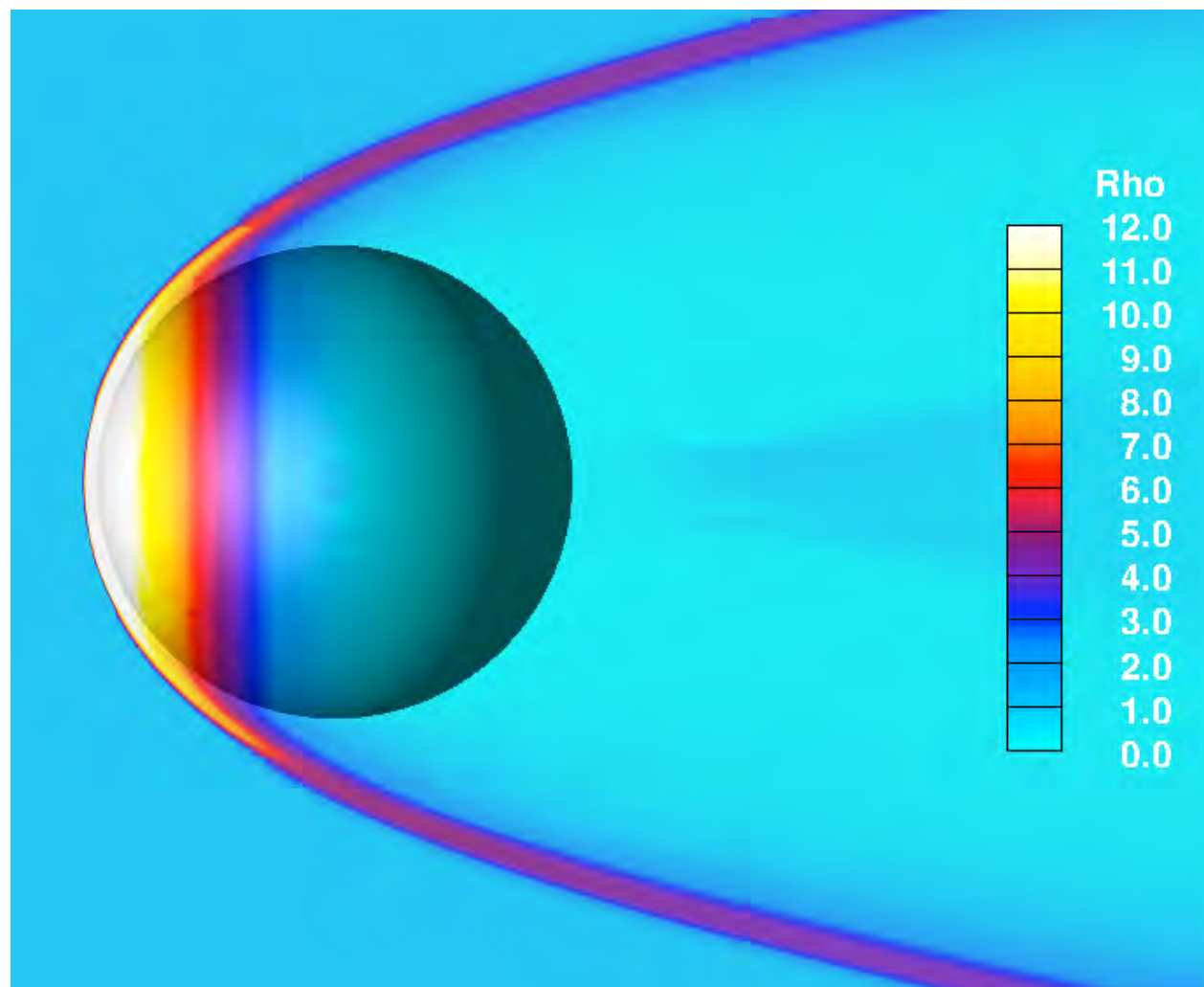
$d = 0.07 \text{ m}$

"Rock"

- Rock shape is an arbitrary surface deformation of the sphere
- Examine the influence of shape on pressure signature

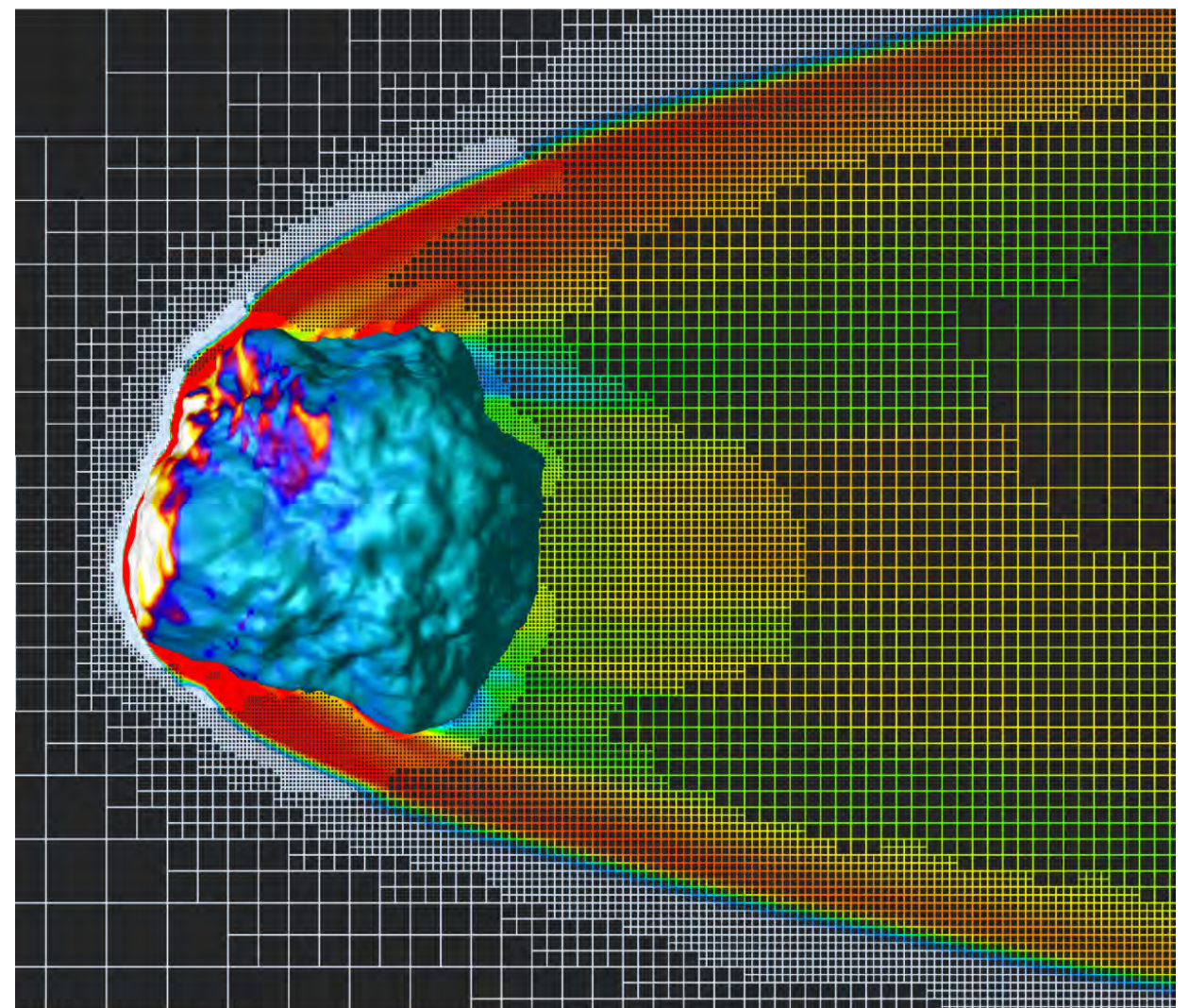


Near-body Flow Solutions (M=48)

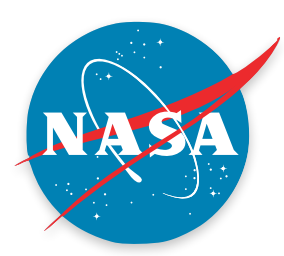


Density Contours

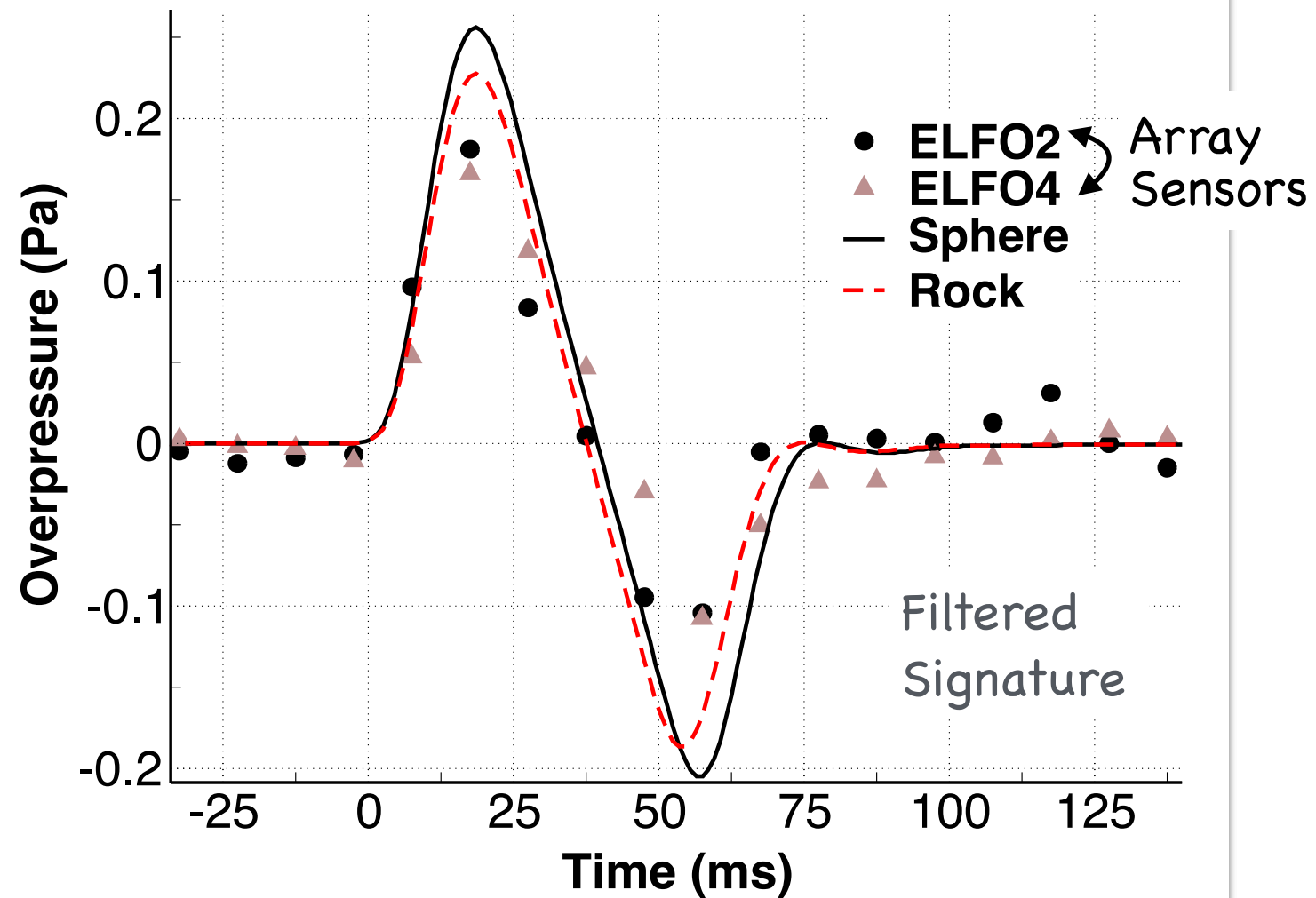
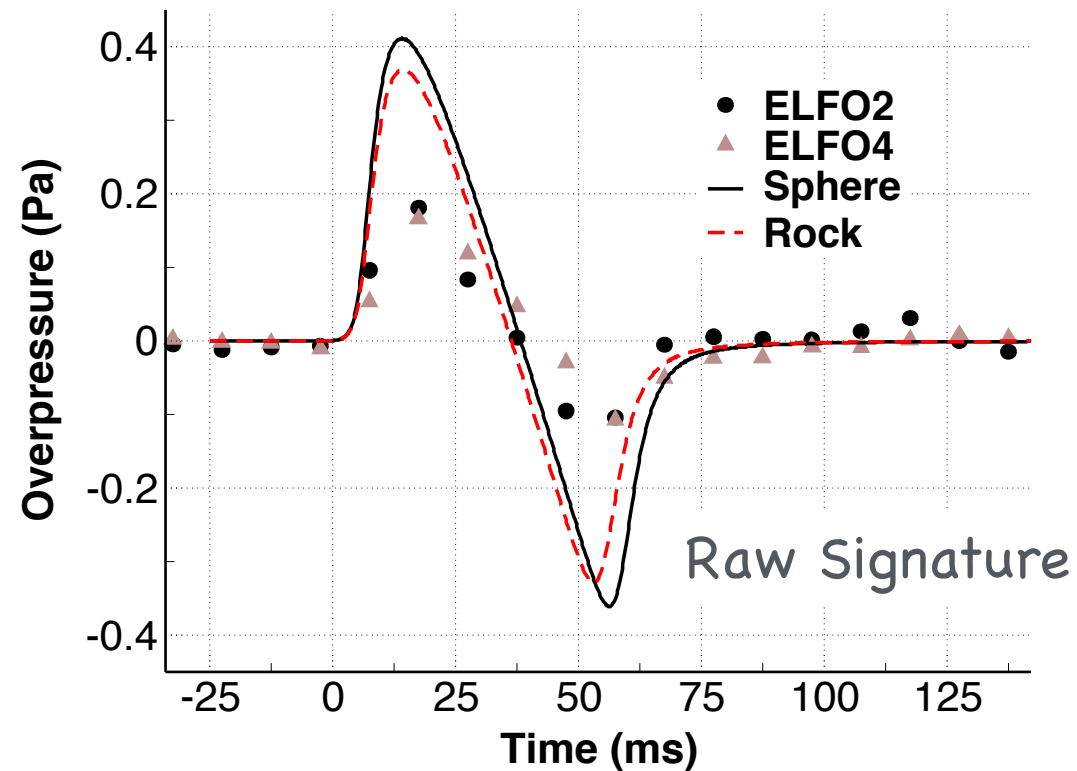
Mesh colored by pressure,
body colored by C_p



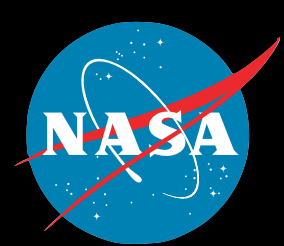
Final mesh size 80-90 million cells



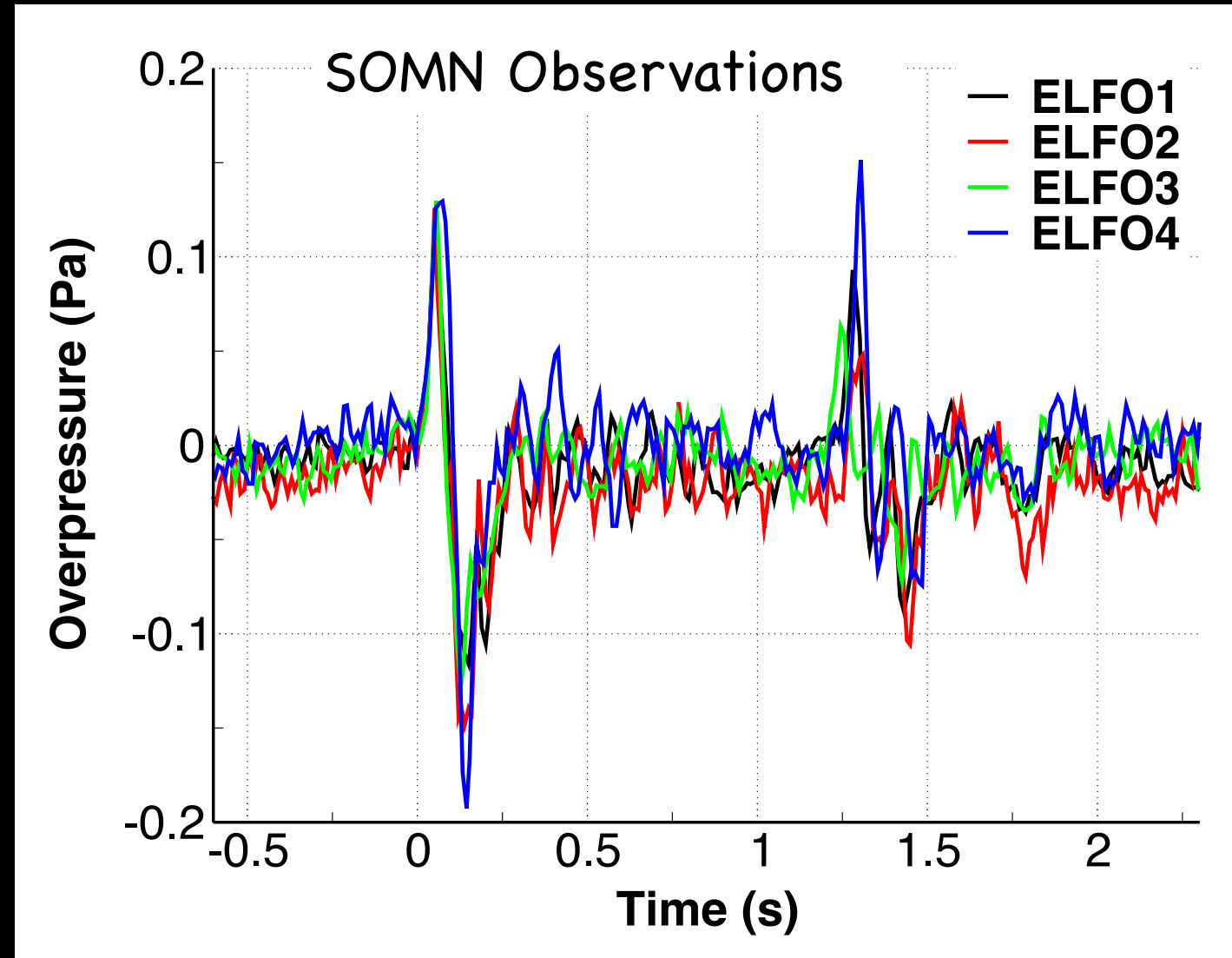
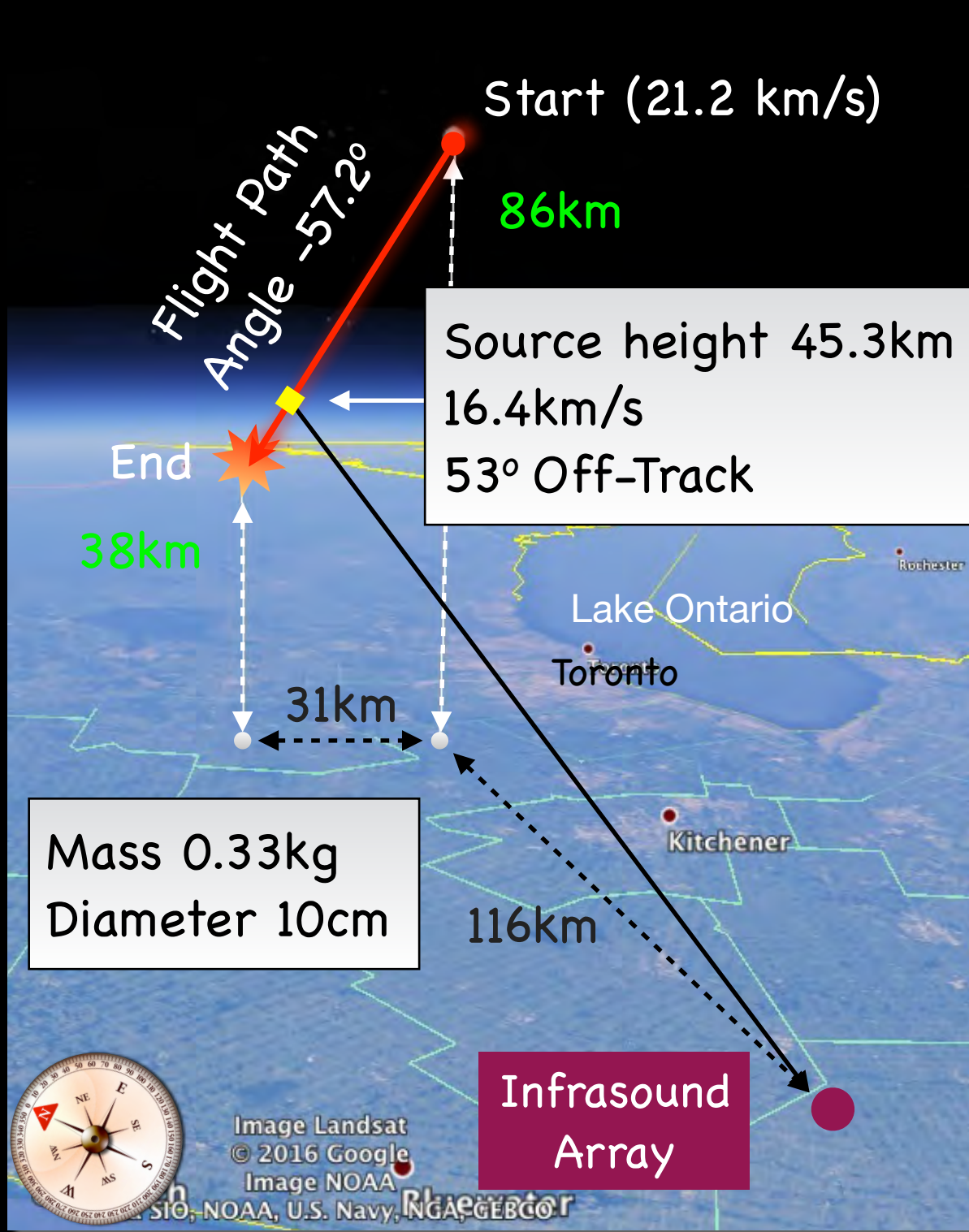
Comparison with SOMN Observations



- Observations filtered with 1 Hz high-pass
- Simulation scaled and filtered same as Stardust
- Excellent prediction of rise time, positive-phase duration and period
- Similar over-prediction of zero-peak and peak-to-peak amplitudes as in Stardust
 - Can be slightly improved by including minor deceleration and ablation
- Validates photometric mass estimate!

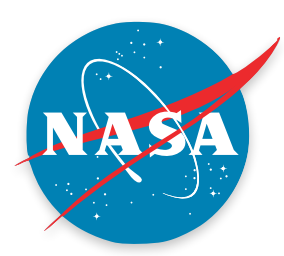


Meteor 20090428



Sensors show 2 distinct arrivals

- Assume one is specular while the other is from fragmentation
- Can simulation identify the specular arrival?

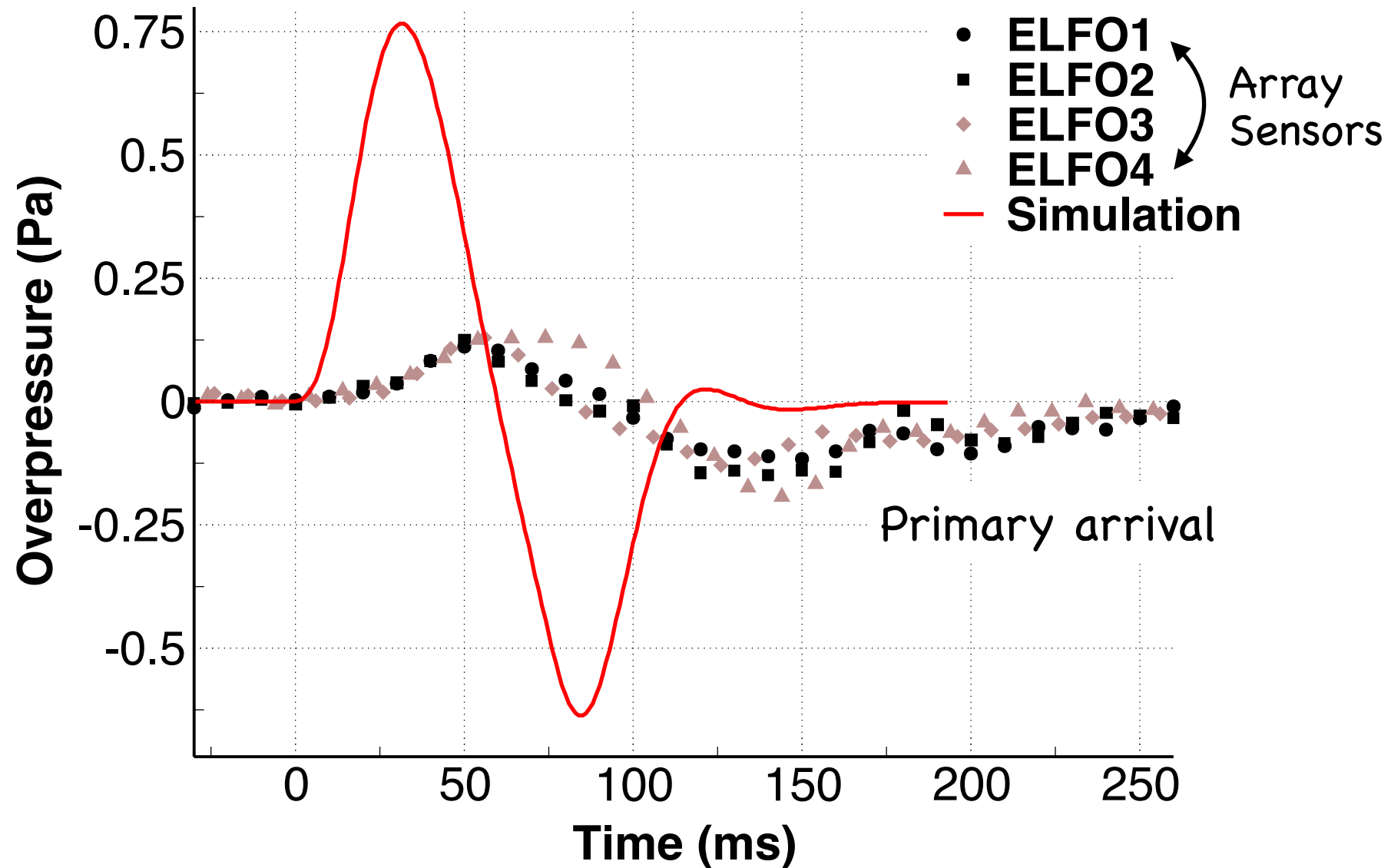


Ground Signature from 45.3km (M=50.2)

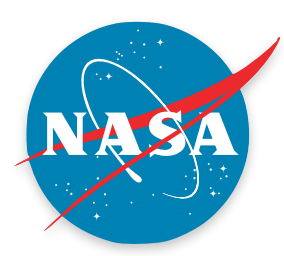
Flight Path -57.2°

Off-track 53°

16.4 km/s

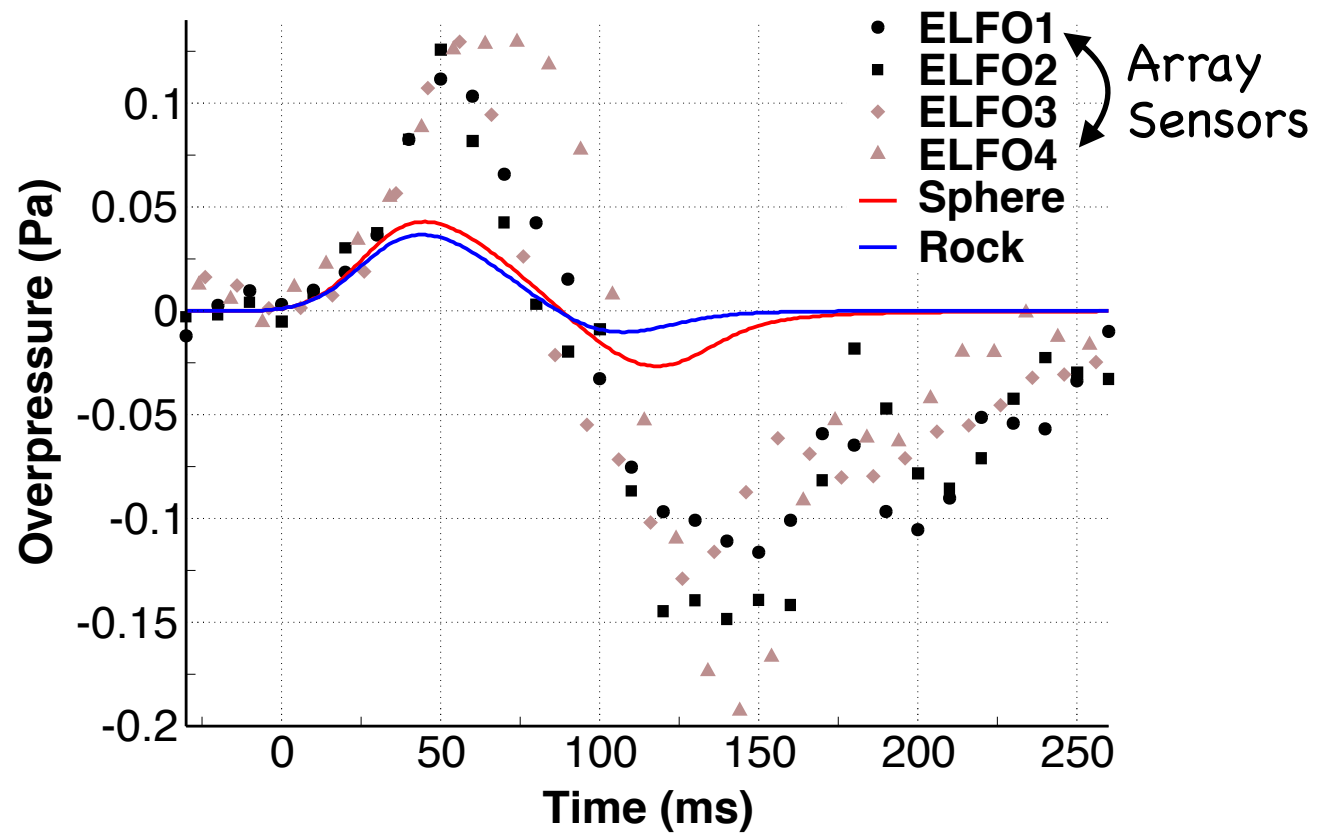


- Signature from specular (geometric) source height does not match observations
 - Search higher — 70 and 60 km — to identify source height

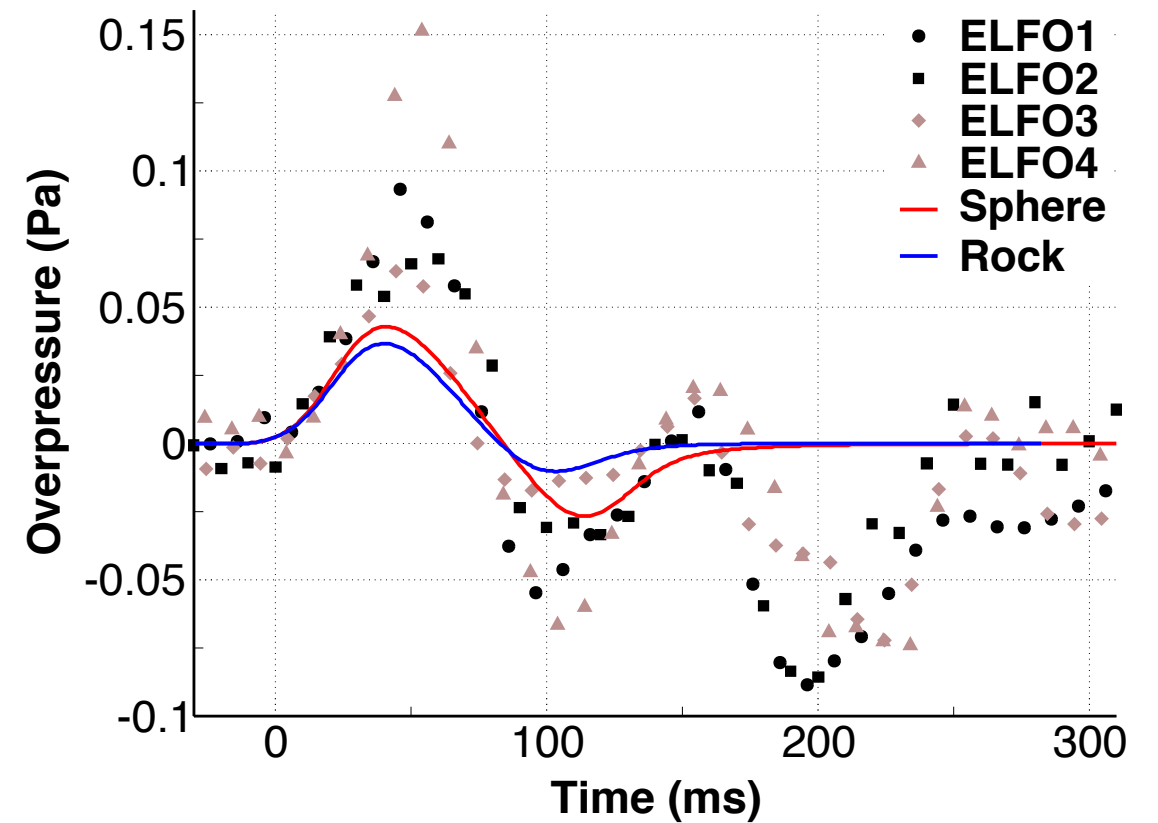


Ground Signature from 70km (M=71.6)

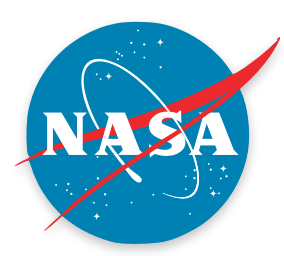
Primary Signal



Secondary Signal

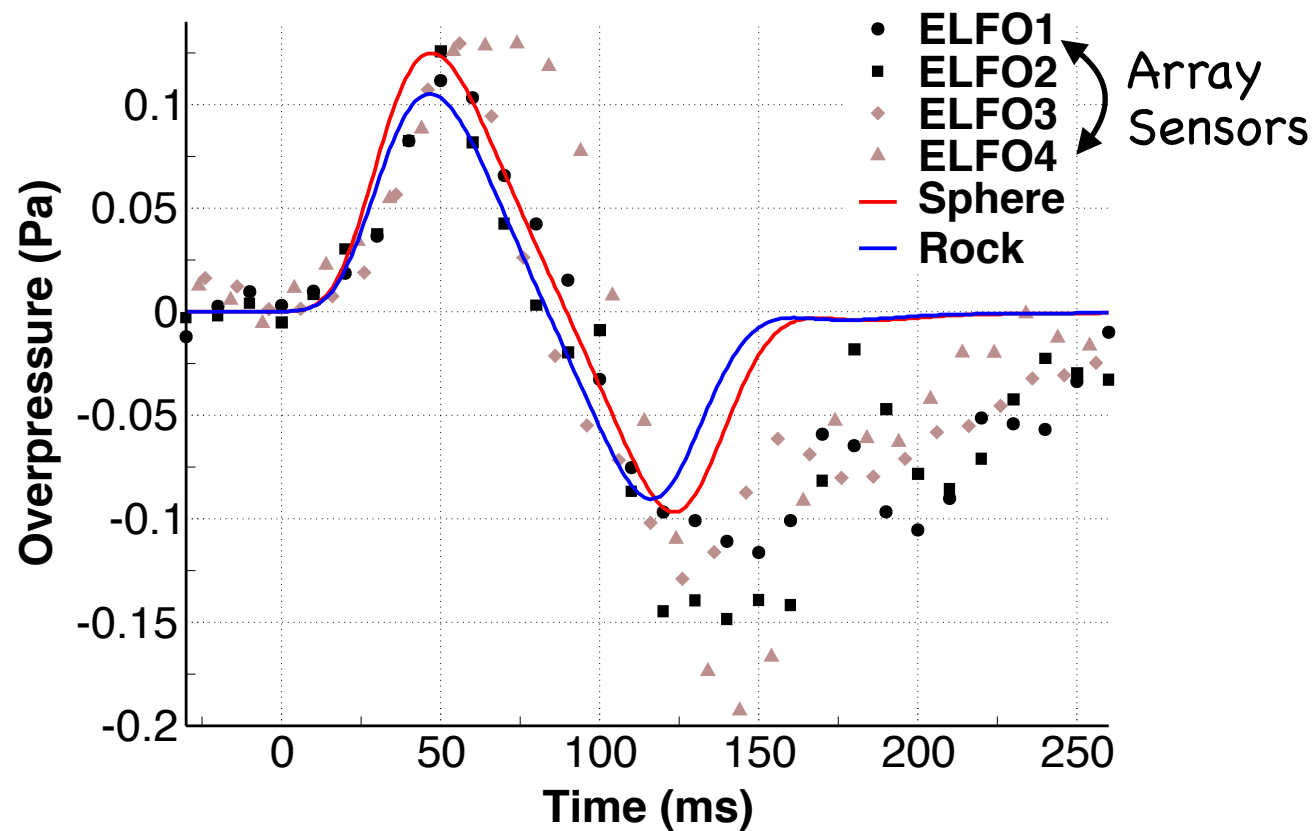


- Positive-phase duration matches both signatures well
- Predicted amplitude is much lower than observations
- 70 km height is too high

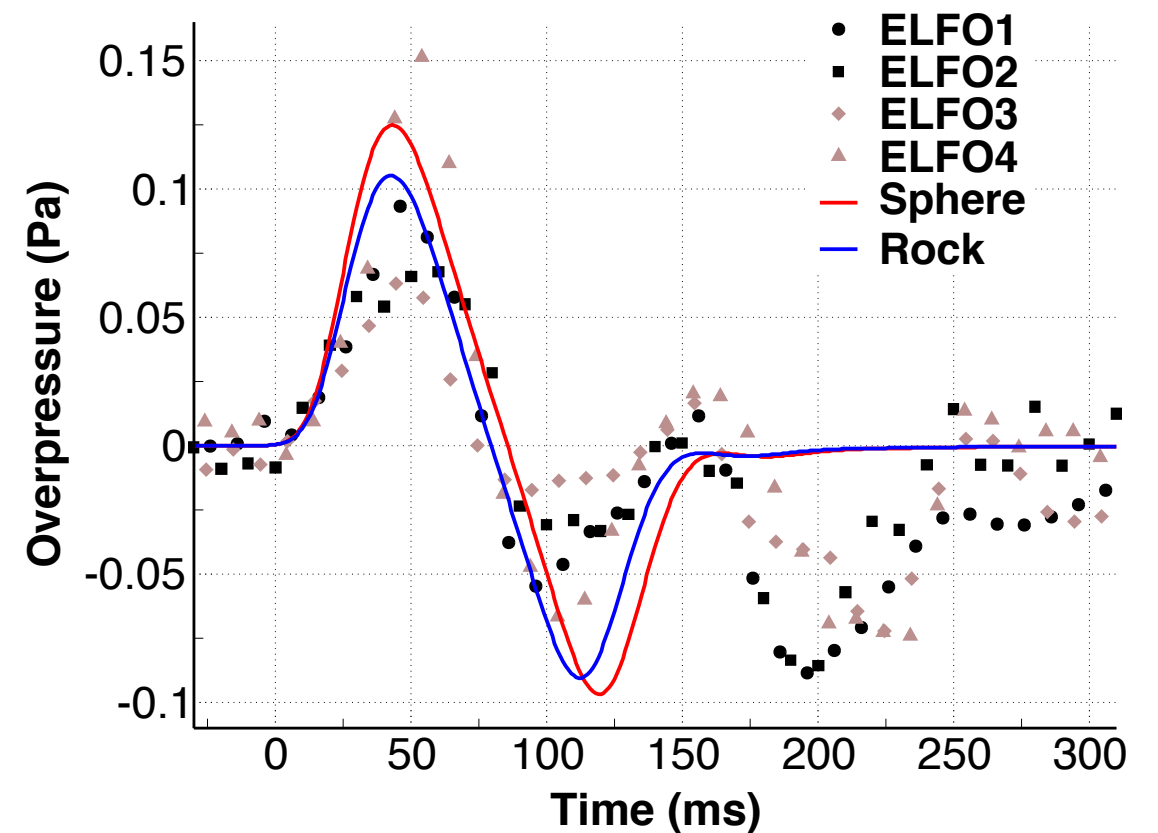


Ground Signature from 60km (M=67.1)

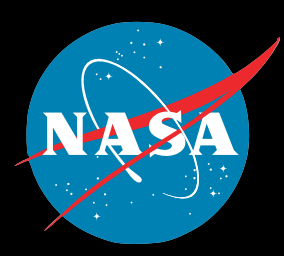
Primary Signal



Secondary Signal



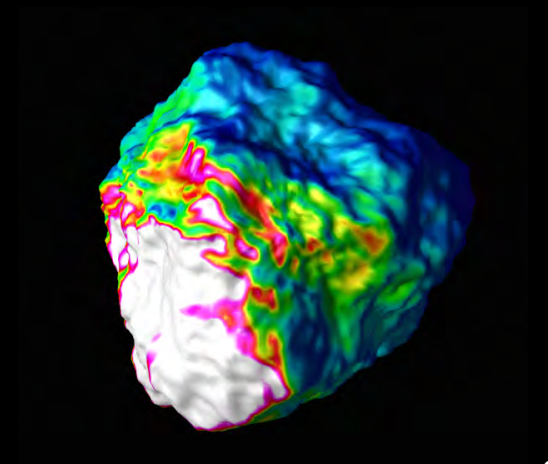
- Rise time and positive-phase duration match both signatures well
- Deep expansion and slow recompression of the primary signal is not captured
- Primary signal: lower altitude fragmentation?
- Secondary signal: higher altitude specular arrival?

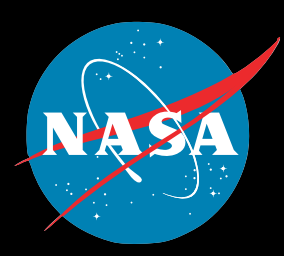


Summary

First validation of numerical simulations that predict meteoric pressure signatures

- Stardust entry verified proposed approach
 - Instrument local response remains an open question
- Completed two meteor cases: SOMN 20081028 and 20090428
 - Filtered signatures show excellent agreement in rise time, positive-phase duration and amplitude
- Promising approach to help interpret meteor observations





Acknowledgements

- Asteroid Threat Assessment Project (ATAP) at NASA Ames
- Wayne Edwards (Natural Resources Canada) for Stardust infrasound data
- Russell Franz and Edward Haering (NASA Armstrong Flight Research Center) for Stardust microphone data
- NASA Ames Research Center contract NNA10DF26C